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Architecture and Remote Interaction Techniques for Digital Media Exchange across 3G Mobile Devices

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Architecture And Remote Interaction Techniques For Digital Media Exchange
Across 3G Mobile Devices

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Abstract

For users away from the office or home, there is an increasing demand for mobile solutions that offer effective collaborative facilities on the move. The mobile cellular device, or "smart phone", can offer a ubiquitous platform to deliver such services, provided that its many physical and technological constraints can be overcome.

In an effort to better support mobile collaboration, this thesis presents a contributing Mobile Exchange Architecture (MEA) designed to improve upon the capabilities provided by mobile devices to enable synchronous exchange of digital media during a phone conversation using wireless networks and cellular devices. This research includes the design and development of one such MEA in the form of a fully functional Photo-conferencing service, supporting shared remote interaction techniques, simultaneous voice communication and seamless digital media exchange between remote and collocated mobile users.

Furthermore, through systematic design, experimental evaluations and field studies we evaluate the effects of different shared remote interaction techniques – 'pointing', 'scaling', 'mixed' and 'hybrid' – assessing the task effort required by users when interacting around shared images across resource constrained mobile devices.

This thesis presents a direction for the future development of technologies and methods to enable a new era of scalable always-to-hand mobile collaborative environments.

Author's Declaration

At the time of submission, several sections of work from this thesis have previously appeared (or are scheduled to appear) in peer-reviewed publications. In the following list the full references for these publications are given.

- Yousef, K. and O'Neill, E. [2008]: Preliminary Evaluation of a Remote Mobile Collaborative Environment. In: Proceedings of ACM CHI 2008 Conference on Human Factors in Computing Systems April 5-10, 2008, Florence, Italy. pp. 3267-3272.

- Yousef, K. and O'Neill, E. [2008]: Supporting Social Album Creation with Mobile Photo-Conferencing. In: Proceedings of Collocated Social Practices Surrounding Photos Workshop at CHI 2008 April 5-10, 2008, Florence, Italy.

- Harper, R. Rodden, T. Rogers, Y., Sellen, A. [2008]. Being Human: HCI in 2020, Microsoft Research, Cambridge, UK. pp. 64-68

- Yousef, K. and O'Neill, E. [2007]. Photo-Conferencing: A Novel Approach to Interactive Photo Sharing across 3G Mobile Networks. In: Proceedings of Social Interaction and Mundane Technologies Workshop Simtech 2007, November 26-27, 2007, Melbourne, Australia..

- Yousef, K. and O'Neill, E. [2007]. Sunrise: Towards Location Based Clustering For Assisted Photo Management. In: Proceedings of Ninth International Conference on Multimodal Interfaces, Tagging, Mining and Retrieval of Human-Related Activity Information Workshop at ICMI 2007 November 12-15, 2007, Nagoya, Japan. pp. 47-54.

- Harper, R. Regan, T. Rouncefield, M. Rubens, S. and Yousef, K. [2007]. Trafficking: Design for the Viral Exchange of Digital Content on Mobile Phones at Mobile HCI 2007 September 9-12, 2007, Singapore, Malaysia.

- Collomosse, J.P. Yousef, K. and E. O'Neill, E. [2006]. Viewpoint Invariant Image Retrieval For Context In Urban Environments. In: Proceedings of 3rd European Conference on Visual Media Production, CVMP 2006, 29–30 November, London, UK. pp. 177 - 177.

Research related to this PhD has also appeared on the discovery channel (Yousef, K interview with Anna Choi), BBC Radio 4 and demonstrated in CSCW'08:

- Yousef, K. and O'Neill, E. [2008]: Supporting Mobile Cooperative Services across 3G Cellular Networks. Reception Demo CSCW 2008 Conference on Computer Supported Cooperative Work November 8-12, 2008, San Diego, California, USA.

This research has also received industry coverage e.g. NTT DATA Institute of Management Consulting and the Vodafone Research 1st prize (2007) for outstanding applied research in the field of Mobile Social Networking and Communication.

Acknowledgements

It is said that we learn the most when we undertake projects at the edge of impossibility; we set out on a voyage of discovery, navigating new terrains, searching for that glimmer of hope that will guide us to the answers we seek.

It is with those thoughts in mind my gratitude goes to my supervisor Dr. Eamonn O'Neill for his support throughout my Ph.D. He has throughout taught me what it means to be a researcher and to strive for excellence. But just as importantly, he has constantly allowed my inquisitiveness the freedom to explore new terrains, undertake greater challenges and the invaluable advice and support to make this thesis possible.

Special thanks go to my family for their never ending support and guidance throughout my life; this dissertation is simply impossible without them. I would also like to thank my friends for providing a constant source of encouragement during my graduate study and to all of my participants for contributing their time, effort and valuable feedback.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

3G	Refers to the third generation of mobile phones.
3GPP	3rd Generation Partnership Project
ANOVA	ANalysis Of VAriance
Ajax	Application Programming Interface
CSCW	Computer Supported Cooperative Work
DOM	Document Object Model
GSM	Groupe Spéciale Mobile, original in French, translates into English as the General Mobile System. Because the standard has become global it is also known as Global System Mobile.
GPRS	General Packet Radio Service, a subset of the GSM standard, which enables transfer of packet data
GPU	Graphical Processing Unit
GUI	Graphical User Interface
HCI	Human-Computer Interaction
HTML	HyperText Markup Language
HTTP	HyperText Transport Protocol
HTTPS	Secure HyperText Transfer Protocol
IMS	IP Multimedia Subsystem
IMSI	International Mobile Subscriber Identity
J2ME	Java 2 Platform, Micro Edition

JSON	Java Script Object Notation
MEA	Mobile Exchange Architecture
MVC	Model-View-Controller
MMS	Multi Media Services
OSI	Open Systems Interconnection
PC	Personal Computer
PDA	Personal Digital Assistant
SD	Standard Deviation
UI	User Interface
URL	Uniform Resource Locator
W3C	World Wide Web Consortium
WAP	Wireless Application Protocol
WLAN	Wireless LAN, local area network
UBICOMP	Ubiquitous Computing
UMTS	Universal Mobile Telecommunications Services, a term used for the third generation standards of mobile telephones. Can be regarded as a synonym to 3G (within the contexts of this book)
WWW	World Wide Web, A service developed at CERN Research Centre by Tim Berners Lee in 1989, which makes possible the global distribution of hypertext and multimedia data

Chapter 1

Introduction

“Any sufficiently advanced technology is indistinguishable from magic” Arthur C. Clarke

1.1 Introduction

Today, there are 1.5 billion television sets in use around the world. 1 billion people are on the Internet. But nearly 3 billion people have a mobile phone, making it one of the world's most successful consumer products. April 3, 2008 marked the 35th anniversary of the first public telephone call placed on a portable cellular phone. Martin Cooper (now chairman, CEO, and co-founder of Array Comm Inc) placed that call on April 3, 1973, while general manager of Motorola's Communications Systems Division.

It was the incarnation of his vision for personal wireless communications, distinct from cellular car phones. That first call, placed to Cooper’s rival at AT&T’s Bell Labs from the streets of New York City, caused a fundamental technology and communications market shift toward the person and away from the place.

> *"People want to talk to other people - not a house, or an office, or a car. Given a choice, people will demand the freedom to communicate wherever they are, unfettered by the infamous copper wire." Martin Cooper.*

There has since been a worldwide boom in the penetration of mobile telephony devices that have had a profound effect on the global technologies landscape. Far-reaching cellular voice networks provide the potential for people to make themselves available for phone calls with any person, at any time. Mobile data networks have become more practical in coverage and bandwidth, fostering improvements in offerings that seek to bring the successful communication modalities of the fixed Internet (e-mail, instant messaging and social networks) to the mobile domain.

Figure 1.1 Mobiles are helping some nations leapfrog older technologies.

The efficiencies mobile technologies bring have also boosted development in poorer countries. Developing nations now make up 58% of handset subscribers worldwide. In rural communities in Uganda, South Africa, Senegal and Kenya mobile phones are helping traders get better prices, ensure less waste and are selling their goods faster (according to the United Nations Conference on Trade and Development: UNCTAD).

Advances in mobile hardware have kept pace with that of the mobile infrastructure. Modern handsets ship with high-resolution colour displays, processing power on a par with lower-end personal digital assistants, stereo sound, and most notably an increase in the number of devices supporting integrated digital cameras. According to forecasts from Gartner Inc, worldwide sales of camera phones, which have almost tripled since 2004, will reach 460 million units in 2006, an increase of 43 percent from 2005, and account for 48 percent of total worldwide mobile phone sales. This trend is set to continue, leading to sales of one billion camera phones by 2010 [Gartner 2006].

While the telecommunications industry has been in the business of connecting people for nearly a century, the contribution of new services such as SMS to operators' main revenue stream in addition to the traditional voice capabilities has not only taken operators by surprise but has also put them on the lookout for additional revenue opportunities such as those offered by 3G networks and Multi Media Messaging (MMS).

Evidence however shows that despite heavy investments in 3G networks to drive new services such as MMS, the MMS service has been described as “a flop” [Economist 2006] and SMS still remains the dominant collaborative service globally for 2006, accounting for 56% of end user spending on mobile data services [IDC 2006].

Through “social shaping” [MacKenzie and Wajcman 1985] it is possible to argue that MMS’s picture sending capabilities as opposed to SMS’s texting capabilities, fails to meet user needs. An emerging body of research on cameraphone use [Kindberg, et al. 2005, Van House and Davis 2005] indicates that people want to share images, however image sharing is itself a complex research space, and mobile users are often frustrated when trying to share images remotely and interactively [Aoki et al. 2005].

1.2 Problem Statement and Research Goals

Private and business communication and collaboration is increasingly being freed from temporal and spatial constraints. Many traditional ways of interacting which required temporal or spatial coordination have given way to much more flexible and adaptive distributed and mobile interaction styles among businesses and people. More and more users are searching the Internet from their phones, and the phone itself is evolving into a computer platform. In the future, there may be no desktop or laptop computers; instead, the only computer you use could be the mobile phone.

The need for continuous collaboration irrespective of physical location and organizational boundaries is becoming a typical setting which produces new complex scenarios that have to be supported by technologies combining paradigms from a multiplicity of research areas, such as distributed systems, CSCW, mobile data management, databases, knowledge management and software engineering.

Independently of the business domain, private collaboration has become a hot issue. Virtual communities and so-called “social networks” have enjoyed a tremendous popularity recently and are starting to require functionalities for collaboration in the broadest sense similar to those in business environments. The widespread availability of mobile devices makes support for mobility a rising topic across these domains.

Although mobile devices free users from a socket and cable, mobility brings about a new level of challenge, including time-varying wireless channels and dynamic topology and connectivity.

Weiser introduced the notion of ubiquitous computing in 1991 [Wieser 1991]:

> *"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it." Mark Weiser.*

The heterogeneity of networks, hardware, software, services and information makes it a challenging task to provide a transparent computing system from the user point of view. Mobility means that some of the assumptions of how to create distributed systems are challenged. Wireless network connections are intermittent with varying bandwidth and quality. Mobile devices are resource-weak to allow them to slip into one's pocket and to operate on battery power.

This dissertation is motivated by the difficulties mobile users have in sharing media remotely and interactively with others. The research question this thesis addresses is "*How can we better design systems to support interactive media exchange across resource constrained mobile cellular devices?"*.

1.3 Contribution and significance

Mobile cooperative services are an emerging field of research in providing always-at-hand communication capabilities to users on the go. In an effort to contribute to our understanding of and improve upon the capabilities provided by mobile devices to exchange rich media content between remote participants, this work provides a novel combination of robust mobile systems engineering with an investigation of related user interaction techniques, contributing to the design, implementation and evaluation of digital media sharing solutions in the mobile domain.

A review of the literature on media sharing on mobile phone based devices suggests a need for rich interactivity that simply doesn't exist with current mobile services. Adopting an architecture led investigation into mobile media sharing we developed a complete mobile exchange architecture and functioning end to end system that works across all 3G mobile cellular networks to support the unique properties of cellular mobile environments.

We have also demonstrated the instantiation of this system as a mobile photo-sharing application. Although this is an important example of the kind of applications that can be supported, we intend the underlying architecture and its interaction techniques to be more generically applicable across a range of mobile activities and services.

A robust distributed co-ordination engine is responsible for the management of all active cooperative sessions and supports scenarios from simple media- and location-sharing services to distributed gaming utilising an extensible plug-in systems architecture. The dissertation goes on to provide a comparative evaluation of remote interaction techniques, “Pointing”, “Scaling”, “Mixed” and “Hybrid”, assessing their impact on users’ actual performance and perceptions, helping to advance and inform the design of systems to support digital media exchange across mobile devices.

Unlike much of the previous work in this area, which has largely focused upon desktop based cooperative environments, our solution was designed and built from the ground up and evaluated across resource limited mobile cellular devices. Inspired by rich real-time interactions, we designed and iteratively prototyped a fully functional mobile architecture which supports real time digital media exchange and interactions across collocated and remote mobile cellular devices with the simultaneous use of an active phone call. This dissertation presents the ideation, conceptual architecture, high-fidelity prototyping, evaluation and iterative prototyping of the mobile architecture, engendering new directions for future work in this area.

1.4 Organization of Dissertation

The goal of this dissertation is to investigate how best to support mobile digital media exchange and to design and build an architecture to enable the creation of such mobile services. There are therefore two distinct strands of research that are intertwined in this dissertation. Figure 1.2 summarises how the different chapters of the dissertation relate to each other.

- Chapter 2 discusses related literature. We start with a structured review of computer mediated communication, CSCW, groupware and relevant projects exploring software design and interaction techniques for collaborative environments. We then conclude by covering themes in mobile media exchange practices, their key challenges and design principles. This chapter informs our ensuing discussions and investigations into mobile media exchange and the development of such cooperative solutions.

- Chapter 3 investigates the cellular landscape. As this thesis is primarily about supporting digital media exchange across mobile cellular devices supported by an active voice channel, this chapter is devoted to providing a brief overview of the GSM data networks, their constraints and the challenges each entails in order to facilitate mobile media exchange over cellular networks and devices.

- Chapter 4 builds upon chapter 3, reporting on the design of a layered mobile exchange architecture that provides a bespoke Session Management Engine, Distributed Coordination Engine, Distributed Exchange Engine, Adaptive Throttling Mechanism and development APIs. The outcome of this chapter is a robust mobile architecture on which we can build fully functional mobile solutions that work over existing 3G cellular networks as outlined in the next chapter.

- Chapter 5 builds upon chapters 3 and 4. Here we present a fully functional instantiation of the mobile exchange architecture presented in chapter 4 in the form of a Photo-Conferencing service. We outline the procedure by which the system was built on commodity mobile hardware, describe design decisions and introduce remote gestural interactions that we evaluate at length in the following chapter.

- Chapter 6 builds upon chapter 5. This chapter describes four specific interaction additions to the mobile exchange architecture. The first study provides an evaluation of the remote interaction techniques offered by a photo-conferencing instantiation of our mobile exchange architecture, evaluating differences between remote pointing, scaling and mixed interaction techniques. The second study evaluates a new hybrid interaction technique developed by combining the most successful characteristics of the interaction techniques found in our first study. A third, field-based, study evaluates user engagement with the photo-conferencing service and reports implications for the design of such mobile collaborative services.

- Finally, Chapter 7 concludes this dissertation with remarks related to the original research question and how it has been addressed. This chapter also addresses the limitations of this work, discussing potential extensions and future avenues for related work.

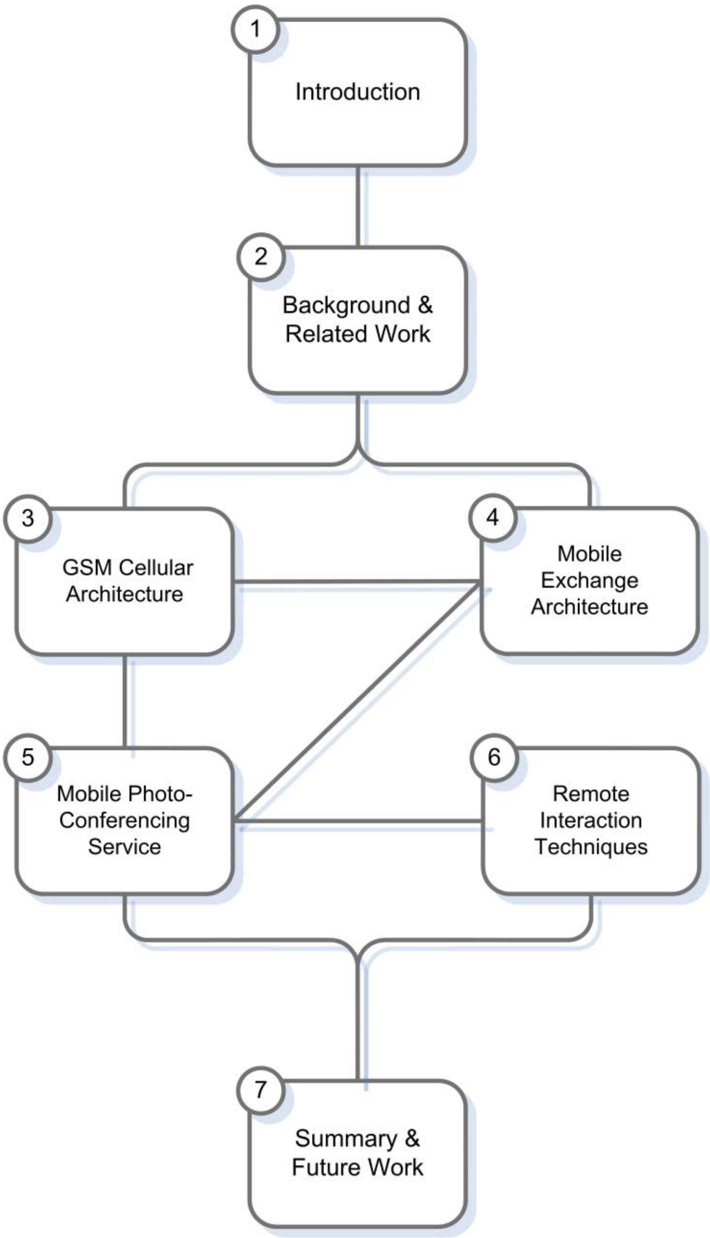

Figure 1.2 Organization of the Dissertation.

Chapter 2

Background & Related Work

"The ecosystem is the computer and collaboration is its operating system" Marten Mickos

2.1 Introduction

Groupware applications typically enable a group of people involved in a common task to manipulate shared objects, and modify them in a coherent manner [Sun et al. 1998]. These systems often incorporate a range of visual and auditory modalities to help groups communicate, cooperate, coordinate, solve problems, compete, negotiate and achieve their goals.

There are many collaborative activities that may be amenable to technological support; examples include telephony, electronic conferencing, knowledge management, distributed communication, media sharing in social settings and collaborations between field- and office-based colleagues.

The objective of this literature review is to provide a background to the various threads of research which are important for framing the research questions and the experiments that constitute the core of this thesis. This chapter covers the role of video mediate communications, mobile media exchange and the issues that brought researchers to design numerous technologies to support remote communication. The goal of this chapter is to help inform our ensuing discussions and investigations concerned with media sharing on mobile devices and the development of mobile cooperative solutions.

Table 2.1. Space and time taxonomy for computer-supported cooperative work, with example applications [Ellis, et al. 1991]. Participants may be in the same place or different places, and may interact synchronously or asynchronously with each other.

		Space	
		Same	Different
Time	Same	Face-to-Face (Presentation Support)	Synchronous Distributed (Videophone)
	Different	Asynchronous (Physical Notice Board)	Asynchronous Distributed (E-mail)

2.2 Collaboration

In the broadest definition collaboration refers to any activities that a pair of individuals or a group of people perform together. However, it can be helpful to define collaboration more precisely. Roschelle and Teasley [1994] define collaboration as a

> *coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem.*

Roschelle and Teasley [1994] also provide a definition of the difference between cooperation and collaboration:

> *Cooperative work is accomplished by the division of labour among participants, as an activity where each person is responsible for a portion of the problem solving. We focus on collaboration as the mutual engagement of participants in a coordinated effort to solve the problem together.*

Furthermore within Computer-Supported Co-operative Work (CSCW), collaboration stresses the idea of co-construction of knowledge and mutual engagement of participants. In this sense, collaboration can be considered as a special form of interaction, with CSCW collaborative applications falling into one of four groups (see Table 2.1), depending on whether the participants are in the same place or different places, and whether they interact in real-time or through a series of disconnected events [Ellis *et al.* 1991].

Although it is tempting to think that the goal of a system for synchronous remote collaboration should be purely to imitate a face-to-face conversation, this may not always be the case as outlined in the next section and there may be more effective ways to support many types of collaborative tasks, which may also exploit more effectively the strengths of the electronic medium [Hollan and Stornetta 1992].

2.3 Video-Mediated Communication

Video-mediated communication (VMC) refers to the tools and technologies that provide collaborators with visual and auditory access to remote spaces. Early video-mediated communication has been around since the late 1920s and it has undergone many sequential technological shifts influenced by the latest hardware advancements and the rapid growth in Internet connectivity that have enabled new forms of remote collaboration, conferencing and distance learning [Finn *et al.* 1997].

Two streams of VMC research have emerged in parallel, both supporting synchronous communication between participants. The earliest work focused on the replication of face-to-face communication through the use of the communication links to transmit facial images (a.k.a. talking heads), providing what Buxton [1992] calls personal space. The second shifted the focus away from facial images and utilised the communication links to transmit information or video of the task being undertaken: 'task space' (Figure 2.1).

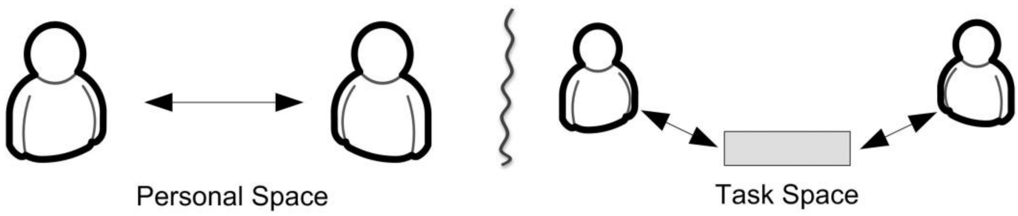

Figure 2.1: Person space versus task space: (left) a personal space is provided by a video link directly between two users; (right) a task space is a new domain in which the users can collaborate.

Understanding the relevance of video communication for different tasks provides a better understanding to why early services such as the 'Picturephone' described in the next section failed to take off and prevent such mistakes from being made to future mobile collaborative services.

In the next section we provide a brief overview of past VMC research aimed at sustaining collaborative work at a distance through video-mediated-communication. This section provides a comparison between the use of VMC across personal and task space that is relevant to our research on mobile collaboration. A more through overview of this area is provided by Finn et al. [1997] and by Kirk [2006].

2.3.1 Personal Space: Video-as-Presence

As early as 1926, scientists at Bell demonstrated a telephone that transmitted a video image along with the audio. Termed the Picturephone, this contraption was considered the logical next step for communication technologies; seeing as well as hearing the person you were talking to would bring the experience closer to being face-to-face and was "premised on the hypothesis that the more closely they mimic face-to-face communication, the more effective the communication that will take place" [O'Conaill *et al.* 1993; p. 391].

The Picturephone was introduced publicly at the 1964 World Fair (see Figure 2.2). Its intuitive appeal fuelled positive forecasts of wide-scale adoption [Egido 1988] that lead to predictions that it would replace the existing voice-only telephone by the early 1970s. AT&T's Picturephone was a prime example of the use of video to create a sense of presence (commonly referred to as Video-as-Presence) by transmitting images of a person's face and shoulders. Video-as-Presence is still in use today and can be seen in such internet applications as Apple's iChat (see Figure 2.3) and Microsoft Live Messenger.

Products incorporating video-as-presence, such as AT&T's Picturephone have, however, been unsuccessful in attracting consumers and have displayed only a gradual growth among business customers [Whittaker 1995]. While often the goal of implementing video-as-presence is to improve communication and to reduce or eliminate employee travel, the results are often disappointing.

A number of recent studies attempting to understand the reasons for its relative lack of success [e.g. Dourish *et al.* 1996, Finn, et al. 1997, Gaver *et al.* 1993, Heath and Luff 1991, Sellen 1995, Tang 1992, Whittaker 2003] have shown that there is generally a preference among users for richer communication that includes video [Anderson *et al.* 2000, Fish *et al.* 1992, Tang and Isaacs 1992], but current devices are often hampered by important limitations that can introduce negative artefacts that can compromise the interaction.

Figure 2.2: AT&T's Picturephone, unveiled at the 1964 World's Fair.

Figure 2.3: Apple's iChat software.

There are, however, modest indications that video-as-presence enhances social and emotional aspects of communication, creating stronger feelings of connectedness between participants [Short *et al.*]. Further benefits provided by video-as-presence include the availability of nonverbal feedback and attitude cues, and access to a gestural modality for emphasis and elaboration [Anderson *et al.* 1997, Isaacs and Tang 1994, Isaacs and Tang 1997].

Further, when there are lapses in the audio channel, the visual channel shows what is happening on the other side, providing important context for interpreting the pause [Isaacs and Tang 1994]. This ability to continually validate attitude and attention may be the reason why video-as-presence has been shown to particularly benefit social tasks, involving negotiation, bargaining and conflict resolution [Anderson, et al. 2000, Whittaker 1995, Williams 1977].

Isaacs and Tang [1992] have also found that incorporating video in remote interactions may support non-verbal communication and the mechanics of conversation, such as turn taking, monitoring understanding and adjusting to reactions. People are also more willing to hold delicate discussions over video than over the phone, and for many, being able to establish the identity of the remote partner is important [Isaacs and Tang 1997].

Groups that use video-as-presence tend to like each other better than those using audio only [Whittaker and O'Conaill 1997], though systems often fail to properly provide cues to the social context of the interaction, such as whether a conversation is public or private (you cannot see who is in the room outside the view of the camera), preventing users from framing their interactive behaviours [Lee *et al.* 1997].

Additionally many important limitations of VMC prevent it from achieving the full benefits of face-to-face. Turn-taking and floor management is difficult in groups because it relies on being able to judge exact gaze direction, something that most video-as-presence systems don’t support [Isaacs and Tang 1994, Whittaker and O'Conaill 1997]. Judging a collaborator’s exact focus of attention when observing or helping with a task is difficult for the same reason [Neale *et al.* 1998]. Side conversations cannot take place and any informal communications have been shown to be extremely difficult to support [Nardi and Whittaker 2002]. Pointing and manipulation of actual shared objects is troublesome [Isaacs and Tang 1994, Neale, et al. 1998].

Further, a number of variations on the classic video conferencing system have been developed, each attempting to address some of the limitations mentioned above. For instance, to provide correct gaze cues, Sellen et al. [1992] developed a Hydra prototype (see Figure 2.4) in which a camera, display, microphone, and speaker are integrated. The displays are small and the cameras positioned to maintain eye contact.

Figure 2.4: The Hydra four-way teleconferencing system.

There are also social and practical barriers to the use of video telephony. Social barriers relate to people's concerns about privacy and a reduced ability to control presentation of the self with video (though long term experiments with media suggest some of these concerns may disappear as video mediated relationships develop with time and in appropriate cultural contexts, [e.g. Dourish, et al. 1996]. Practical barriers to use in organisational contexts include the need to plan calls too far in advance, technical difficulties of setup and the need to use special equipment in dedicated rooms [Hirsh *et al.* 2005]. If the required effort is too high, people resort to the simpler and more widely available audio telephony [e.g. Martin and Rouncefield 2003, Tang 1992].

For tasks that primarily involve information exchange or simple problem solving the benefits of adding video have been investigated and it has been found that comparisons of video-as-presence and audio-only have generally not shown any benefits of video over audio-only communication [Anderson, et al. 2000, Tang and Isaacs 1992]. There is however demonstrable value of video to visually share objects in support of conversation between remote participants, rather than simply to share 'talking heads' [e.g. Kraut *et al.* 2002, Whittaker 2003]. Studies of the effects on communication in mediated environments have shown that sharing the same visual space (task-space) is an important aspect of communication [Sellen 1995, Stefik et al. 1987].

2.3.2 Task Space: Video-as-Data

The field of video mediated communication has long examined the effects of providing visual information to aid people in collaboration over distances; recent research shows however that not all forms of visual information is sufficient to aid in the communication process. Examples such as the introduction of video telephony in the 1960s followed confident predictions that it would eventually replace voice only telephony but, as history and the benefit of hindsight has revealed, those predictions didn't bear out but eventually lead to several market failures [Harper and Taylor 2005].

A number of parallel studies of video mediated communication through "personal spaces" have investigated the additional utility of the technology to create "task spaces", where images of the work objects themselves are transmitted between participants [Anderson, et al. 2000, Fussell *et al.* 2000, Gaver, et al. 1993, Nardi *et al.* 1993]. These studies were in response to a growing body of evidence that questions the importance of personal space in providing video as the form of presence (e.g. talking heads). Whittaker [1995] argued that the research into the use of video has focused too much on supporting non-verbal communication and has neglected functions such as using visual information to initiate communication or depicting shared work objects.

Early research on task spaces was conducted by Krauss and Fussel [1990, 1991] concerning the development of mutual knowledge and the construction of shared communicative environments for increasing communicative effectiveness. They utilised an experimental design aimed at exploring the process of achieving grounded conversations through the design of different communication technologies.

Rochelle and Teasley for instance, demonstrated that collaboration requires the construction and maintenance of a shared representation of the problem and stressed the role of shared understanding, and wrote that collaboration is "a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem" [1994; p. 70].

The research has demonstrated that collaboration requires the construction and maintenance of a shared representation of the problem [1994], that including a shared task space is important [Buxton 1992] and for tasks other than negotiation a task space is more useful than a personal space [Anderson, et al. 2000]. Shared task spaces were also found to be fundamental for coordinating awareness, through the "understanding of the activities of others" [Dourish and Bellotti 1992], which in turn provides a "context for your own activity" [Dourish and Bellotti 1992: 107].

Further, in collaboration, grounding is part of a refinement process through which actors refine what they mean, becoming more and more exact over time [Baker 1995]. They increase their common ground when they add new related information. This is done through the tools, the goal, the setting, or the individuals themselves [Baker *et al.* 1999] and that the constraints on achieving common ground, and the costs of doing so, change in the collaborative situation depending on the tools being used. Task space was found to facilitate the negotiation of 'common ground' and a level of shared understanding of what is being discussed in a conversation between two or more parties [Clark 1992, Fussell, et al. 2000]. In an effort to explain this finding, later work [Gergle *et al.* 2004] demonstrated through sequential analysis how visual actions within a shared space can be used to replace elements of dialogue that would be necessary in the absence of visual feedback.

Kraut, Gergle, and Fussell in their experimental setup (see Figure 2.5) demonstrated that the presence of a shared visual space significantly improved performance on the collaborative puzzle task [Kraut, et al. 2002]. The authors controlled whether the helper could see the space of the worker and could refer to the objects by the mean of 'deictic expressions'. The puzzle based approach was taken to allow systematic manipulations to be made to the shared visual environments such that various parameters of their construction could be empirically compared.

Through their experimental analyses Krauss and Fussell [1990] began to understand how task-focussed language evolved during the collaborative tasks. The evolution of referring expressions and the developing awareness of common referents was shown to be significantly affected by the resources used to establish communication. If a shared visual environment was enabled it was often observed to be of significant support to the smooth establishment of such critical communicative processes. In their early work on the subject [Gergle *et al.* 2004, Kraut, et al. 2002], they demonstrated that the presence of the shared visual space significantly improved performance on the collaborative puzzle task and that interactional references further enhanced remote collaboration [Kraut et al. 1996].

Gergle, Millen, Kraut and Fussell [2004] extended this finding by demonstrating that when the talk in collaborative tasks is mediated by text-based chat (such as Instant Messaging), persistence of the text messages improves task performance but less so than access to a shared visual space. Through a series of sequential analysis techniques [Bakeman and Gottman 1997, Bakeman and Quera 1995, Fienberg and NetLibrary 1980, Fussell *et al.* 2004] they also demonstrated how action can replace explicit verbal instruction in a shared visual workspace. They revealed that pairs with a shared workspace were less likely to explicitly verify their actions with speech. Rather, they relied on visual information to provide the necessary communicative and coordinative cues.

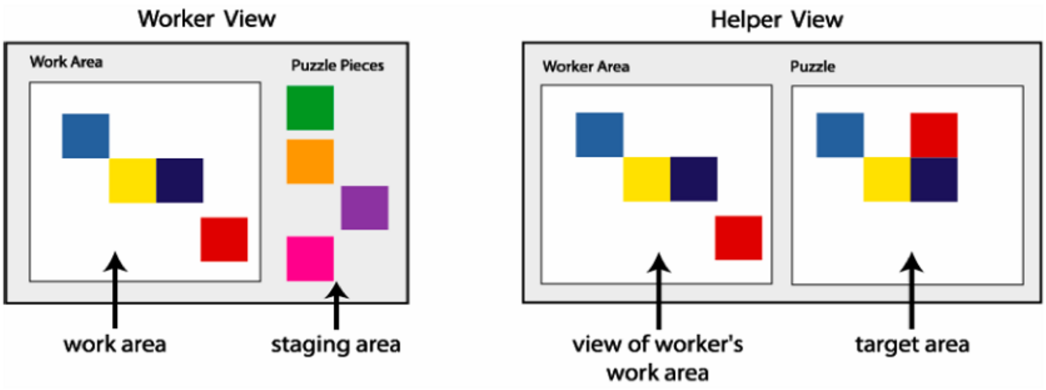

Figure 2.5: The collaborative puzzle task. The Worker's view (left) and the Helper's view (right) from Gergle (2006) The Worker's screen consists of a staging area on the right hand side in which the puzzle pieces are shown, and a work area on the left hand side in which she constructs the puzzle.

Recent research has shown that sharing a 2D visual space improves instruction in computer-based tasks [Karsenty 1999, Kraut, et al. 2002]. Other research has suggested the value of workspace oriented video systems for 3D tasks [e.g. MacWhinney 2000, Nardi, et al. 1993]. These studies suggest the importance of shared views of the workspace for remote collaboration on physical tasks and suggest that video systems which provide views of the work area are likely to be more useful in supporting awareness and grounding during collaborative physical tasks.

2.4 Towards Mobile Collaboration

An important emerging aspect is that people are mobile and do much of their work away from their office. In response, Bellotti & Bly [1996] suggest that systems for collaborative work should be designed to support mobile collaborators. In this section we examine the current drivers of mobile collaboration and the limitations imposed by the technology and usability that has to date limited its widespread adoption.

The mobile phone initially started out as a hardware centric device and what you did with it was very limited, but making it small, cheap and sleek were key factors in its ever rising success. Mobiles are now converging to become software driven devices. That is not to say that the hardware is no longer important but the balance of what makes it useful and attractive is shifting to the software. Companies such as Apple, Google, Nokia, RIM and Microsoft are depending more on the added value afforded by software to create more compelling consumer solutions. Mobiles now account for a third of the top three items people carry with them whenever they leave home in addition to keys and wallet [Ichikawa *et al.* 2005].

Although mobile services that have collaborative elements have long been provided by mobile phone companies in the form of voice calls, text messages and more recently 3G multimedia messaging (MMS). Their collaborative capabilities have been limited to the use of one channel at a time, with voice communication still the only real-time collaborative service available on cellular devices today.

In an effort to contribute to mobile phone based collaborative architectures, we sought to improve upon the capabilities provided by mobile devices to exchange rich media content between remote participants. The following literature review on media sharing across mobile cellular devices suggests a need for collaborative interactivity that simply doesn't exist with current mobile services.

2.5 Mobile Media Exchange

There has been a worldwide boom in the penetration of mobile telephony devices that have had a profound effect on the global technology landscape. Far-reaching cellular voice networks provide the potential for people to make themselves available for phone calls with any person, at any time. Consumer mobile data networks have become more practical in coverage and bandwidth, fostering improvements in offerings that seek to bring the successful communication modalities of the fixed Internet (e-mail, instant messaging and social networks) to the mobile domain.

Advances in mobile hardware have kept pace with those of the mobile infrastructure. Modern handsets ship with high-resolution colour displays, processing power on a par with lower-end personal digital assistants, stereo sound, and most notably an increase in the number of devices supporting integrated digital cameras. According to forecasts from Gartner Inc, worldwide sales of camera phones, which have almost tripled since 2004, will reach 460 million units in 2006, an increase of 43 percent from 2005 and account for 48 percent of total worldwide mobile phone sales. This trend is set to continue, leading to sales of one billion camera phones by 2010 [Gartner 2006].

While the telecommunications industry has been in the business of connecting people for nearly a century, the proliferation of new services such as SMS and their impact on operators' main revenue stream in addition to the traditional voice capabilities has not only taken operators by surprise but has also put them on the lookout for additional revenue opportunities such as 3G networks and Multi Media Messaging (MMS).

With more and more people capturing photos on the move, camera phones account for a large number of the photos we carry around with us. Research suggests that technologies are becoming increasingly suitable for supporting collaboration around photos, and may potentially offer new forms of expression [Lindley and Monk 2008]. Evidence however shows that despite heavy investments into 3G networks to drive new services such as MMS, there has been relatively little use. The MMS service has been described as "a flop" [Economist 2006] and SMS remained the dominant collaborative application globally for 2006, accounting for 56% of end user spending on mobile data services [IDC 2006].

Through "social shaping" [MacKenzie and Wajcman 1985] it's possible to argue MMS's picture sending capabilities, as opposed to SMS's texting capabilities, fails to meet user needs. An emerging body of research on cameraphone use [Kindberg, et al. 2005, Van House and Davis 2005] indicates that people want to share images, however image sharing is itself a complex research space, and mobile users are typically frustrated when trying to share images remotely and interactively [Aoki, et al. 2005].

2.6 Mobile Capture Culture

Studies of cameraphone use paint a picture of successful adoption and creative appropriation, e.g. teasing [Kurvinen 2003], collaborative storytelling [Koskinen *et al.* 2002] or the mundane "elevated to a photographic object" [Okabe and Ito 2003]. It appears that as relationships get more intimate, shared messages tend to get even more mundane. While friends and acquaintances tend to capture and share moments, events and observations that are at least minimally interesting for the recipient, couples tended to share pictures and sounds about almost anything they happen to see or hear just to maintain a state of closeness through "visual co-presence" [Ito 2005].

Most intriguing, perhaps, are the breadth of ways that users have appropriated photographs in computer-mediated communication technologies. Mäkelä et al. noted that photos were used for joking, expressing emotion, and sharing art [Mäkelä *et al.* 2000]. Ling and Julsrud [2004] identified six genres of use including documentation of work-related objects, visualization of details and project status, snap shots, postcards, greetings and chain messages.

Investigating emergent practice of camera phone use in Japan, Okabe employed ethnographic diary studies of camera phone usage patterns and identified three social usages of cameraphones: archiving, intimate sharing, and peer-to-peer news and reporting [Okabe 2005]. Kindberg et al. [2005] conducted a study into how and why people used cameraphones in both the UK and US in which they proposed a taxonomy of image

Table 2.2. A taxonomy of image capture, showing numbers and proportions of images by category [Kindberg et al. 2005].

	Social				**Individual**	
Affective	**Mutual Experience.** Images used to enrich a shared, co-present experience (either in the moment or later as a memento).	103 (35%)	**Absent Friends or Family.** Images used to communicate with absent friends or family (either in the moment or later).	63 (21%)	**Personal Reflection.** Images used for personal reflection or reminiscing.	120 (41%)
Functional	**Mutual Task.** Images shared with people co-present in support of a task (either in the moment or after the event).	11 (4%)	**Remote Task.** Images used to help accomplish a task by sharing with remote family, friends or colleagues (either in the moment or later).	23 (8%)	**Personal Task.** Images used to support some future task not involving sharing.	29 (10%)

capture (see Table 2.2) that categorised images based on their social or individual uses and whether they were of an affective or functional nature.

Van House also focused on identifying classes of pictures taken and shared by cameraphone users [Van House and Davis 2005]. Reporting on a 60-person study conducted over 10 months of an experimental Mobile Media Metadata (MMM2) system, Van House and Davis pinpointed four pre-existing practices from traditional photography that their participants adapted for cameraphone use: creating and maintaining social relationships, constructing personal and group memory, self-presentation and self-expression. In addition they identify two emerging categories: social commentary, e.g. journalistic shots, and functional uses, e.g. scanning written information.

Voida and Mynatt [Voida and Mynatt 2005] noted that nearly two-thirds of the photos captured by their participants were that of the classic Kodak Culture [Chalfen 1987] and by at large, mobile multimedia seems to continue this tradition of ordinary snapshot photography, but makes it even more ad hoc in terms of what people choose to shoot [Koskinen, et al. 2002]. Cooley follows a similar theme in which she proposes that imaging with cameraphones is informed by an autobiographical impulse and, thereby, belongs to a long tradition of first-person forms of documentation [Cooley 2005].

Taylor and Harper adopt an anthropological and social view of cameraphone sharing in terms of the age old practices of 'gift-giving' which they note as simply "great recurrences of ordinary society" and that "successful technologies are ones that afford the accomplishment of particular enduring cultural practices" [Taylor and Harper 2002].

Maia Garau identified seven classes in which shared pictures could be categorised, based on observations of users' emerging cameraphone social practices with 'Radar' [Maia Garau 2006], a system designed to enable visual conversations between close friends. Based on this classification a shared museum picture could be categorised as a contextual photo.

- Context: Location | Activity | Food | Time/Temperature
- Portrait: Self | Friends | Animals
- Visual interest: Scenery | Architecture | Poetic | Art shot
- Media: Logo | Advertisement | Book | TV/film | Website
- Humour: Amusing shot | In-joke | Running joke
- Event: Mundane | Special
- Travel: Information (e.g. boarding card) | Tourist shot

Rivière argues that the act of sharing may be just about communication "Being multimedia tools, they increasingly use intimate play context, which have no rational purpose but rather aim at sensations, and in which the search for immediately shared pleasure is more and more visible" [Rivière 2005].

Koskinen describes cameraphone pictures as merely focusing on immediate life and it is this complexity of immediate life that has lead to many interpretations of use [Koskinen 2007]. He continues to state what people see as important may result from years of symbolic and imaginary work, e.g. while "Paris" may be a sign on the map for one person, for another it may be an elaborate, exciting experience created over years of being there [Battarbee and Koskinen 2005]. In addition messages may be designed using complex constructs. For example, people often take advantage of genres they find from media and culture, including documents, snapshots, postcards, greetings, and chain messages that are sometimes downloaded from the Web [Ling *et al.* 2005].

The breadth of this research on the uses of mobile image capture and sharing highlights the complexities involved, in which any intentions can be defined though several categories at once, for example Barthes talks about a portrait-photograph of himself as related to four versions of himself: the person he thinks he is, who he wants others to think he is, who the photographer thinks he is, and the person the photographer makes use of to exhibit his or her art [Barthes 1981]. In the next section we define a sharper focus for our research here on the digital media exchange capabilities afforded by the mobile capture and share technologies.

2.7 Mobile Sharing Limitations

The recent literature around digital photography often remarks upon two trends. First, there is the desire to move beyond the individual's taking, organising and storing photos to more social practices of sharing images and jointly constructing albums or archival collections [Frohlich *et al.* 2002]. Secondly, there is the increasing use of mobile phone cameras [Ito 2005] to provide opportunistic, spur-of-the-moment capture [Okabe and Ito 2003, Van House and Davis 2005] and to enable the creation of "life documents" [Plummer 2001].

Whether increasingly capable camera phones will precipitate the demise of the consumer digital camera market or fuel it by introducing more people to the joys of digital photography is currently an open question. What is clear, however, is that the sheer number of camera phones in use and their closeness to hand for their typical user makes the camera phone an increasingly common source of the images that people wish to share. However, the very ubiquity of the camera phone and the spontaneous capture of images in a wide variety of settings mean that in many of these settings the user has no access to other devices with which to display and share the captured photos. Hence, moving from capture to sharing can involve the sharers huddling around the camera phone's screen [Kindberg, et al. 2005] or the photo taker posting it to an online archiving service. The former approach has the advantage of maintaining the spontaneity of the photo capture and sharing in the moment. The latter approach has the advantage of providing the sharers with copies, their own displays, tools etc at the expense of spontaneity.

This has led to much research [Aoki, et al. 2005, Ito 2005, Kindberg *et al.* 2004, Maia Garau 2006, e.g. Okabe 2005, Van House 2007] into the limitations of camera phones and services for sharing images, such as MMS which currently remains relatively unused and under developed [Economist 2006]. Subsequent research has been dedicated to overcoming these difficulties [Van House and Davis 2005]. Solutions such as MMM2 [Davis *et al.* 2005] sought to improve on several limitations of MMS, overcoming the size constraints imposed on MMS and streamlining the sharing process. However, the MMM2 system didn't lead to an increase in mobile-to-mobile sharing. Van House describes this as partly due to poor usability of the MMM2 phone interface and partly due to technical difficulties [Van House 2006]. Radar by Maia Garau et al [Maia Garau 2006] was also designed to overcome the limitations of MMS mobile sharing. Similarly to MMM2, Radar provides a mechanism to upload images directly to a web-based archiving solution for sharing images, differing only in its chronological representation and commenting capabilities.

Okabe [2005] reports the "one channel at a time" interaction paradigm of MMS as causing many mobile users to be "frustrated when trying to share images remotely and interactively".

Recent research points to participants needing richer capabilities to connect in the moment, undergoing the effort of using multiple devices to achieve ongoing conversations while sharing images [Kindberg, et al. 2005]. Similarly, mobile users have been observed transferring mobile images to instant messaging clients to enable conversation [Van House 2006]. This need for interactivity when sharing photographs has also been traced back to earlier ethnographic studies of collocated domestic photography by Chalfen, who argued that "[domestic photographs] are meant to be shared, and they are meant to prompt interaction" [Chalfen 1998].

Frohlich et al. [2002] proposed "Photo-Conferencing" as a service that could overcome these restrictions and provide a means by which users could engage in interactive computer-mediated photo-sharing practices, supported by a simultaneous telephone conversation, minimising collaborative effort [Clark and Brennan 1991]. However, current mobile devices and cellular networks present serious challenges to enabling this and previously no mobile cellular photo-conferencing service has been created.

In this dissertation we report on the first such mobile photo-conferencing service. The service we present here allows collocated and distributed 3G cellular users simultaneously to share, interact and converse in a real-time cooperative photo-conferencing session through a single application.

2.8 Chapter Summary

In this chapter we started with an overview of the various strands of research relating to collaboration and the relevance of video communication for different tasks, and covered how face-to-face interaction provides people with many contextual cues such as facial expressions, body postures and gestures that guide them as they interpret others' communication and interact with them [Goffman 1959]. We also saw that in distributed collaboration; depending on which medium is used, some or all of these cues disappear. Still, research has demonstrated that collaborators often find it more important to have a shared view of the work than to see each other [Anderson, et al. 2000, Buxton 1992, Gaver, et al. 1993, Kraut, et al. 2002, 1994]. However, if the team members are not sharing the same native language, video is especially important: the visual link supports them in showing their understanding through facial expressions and gestures [Veinott *et al.* 1999].

In the latter half of this chapter we presented the notion that the proliferation of small portable mobile devices may one day allow for new anywhere, any time collaborative capabilities that don't exist today. Although there has been a growing body of work relating to the impact of video mediated communication on users and desktop environments [e.g. Anderson, et al. 1997, Sellen 1995, Whittaker and O'Conaill 1997], very little research to date has investigated those effects across resource restricted mobile cellular devices that are rapidly becoming the most common form of user facing computing device.

Mobile users are "frustrated when trying to share images remotely and interactively" [Okabe 2005] and the need for interactivity and interaction among participants is not fully met by current mobile and MMS practices.

Our research is motivated by the difficulties mobile phone users have in sharing and engaging with media synchronously and interactively with others. The goal is to explore how we can better design mobile systems to support such sharing and engagement in both collocated and remote settings using resource constrained mobile cellular devices.

These devices also present unique research challenges for enabling those services across limited mobile hardware specifications, restrictive screen sizes and varying cellular networks that are susceptible to signal loss and network outages.

The service we seek to demonstrate will allow both collocated and remote 3G cellular users simultaneously to share, interact and converse in a real-time cooperative session, providing mechanisms through which users can indicate focus [Turner and Kraut 1992] during a digital media session and construct what Crabtree et al. [Crabtree *et al.* 2004] describe as "a host of fine grained grammatical distinctions".

In the following chapters we report on the first such mobile phone based solution. This project entailed a multifaceted challenge that required [1] an understanding of existing mobile technologies; [2] the creation of a mobile exchange architecture that supports the sharing of different forms of digital media (data types) between mobile devices; [3] the development of a mobile media-sharing solution; and [4] the evaluation of interaction techniques to support effective communication through this solution.

Chapter 3.

GSM Cellular Architecture

"The Mobile Web Initiative is important - information must be made seamlessly available on any device" Tim Berners-Lee

3.1 Introduction

The increased need for people and organizations to stay connected whilst changing physical location and crossing organizational boundaries has resulted in a wave of new portable devices, and generated interest in tackling some of the difficult research issues arising in developing technologies for such context.

Mobile cellular devices and the networks on which they operate present new challenges in the forms of bandwidth constraints, intermittent connectivity issues and signal loss that sets them apart from traditional fixed networks. These mobile cellular networks also present many opportunities to utilise the existing infrastructures to provide new services that harness the potential available in today's networks.

This chapter provides the background to the mobile cellular landscape, looking at the existing infrastructure and deployed technologies, outlining limitations to existing technologies and important issues that need to be addressed in an effort to enable rich media exchange across mobile devices and networks. The work reported in the rest of the thesis sets out to overcome many of these limitations and challenges.

3.2 Mobile Communication Systems

The origins of mobile telephony date back to the 1920s, initially used with maritime vessels and not particularly suited to on-land communication. The equipment was extremely bulky, the radio technology did not deal very well with buildings and other obstacles found in cities. Further progress was made in the 1930s with the development of frequency modulation (FM), which helped in battlefield communications during the Second World War. These developments were carried over to peacetime, and limited mobile telephony service became available in the 1940s. Such systems were of limited capacity, however, and it took many years for mobile telephony to become a viable commercial product.

Mobile communications as we know it today started in the late 1970s with the introduction of the first generation wireless systems, characterized by voice only (analogue) communication, with limited support for user mobility. The analogue services provided methods of modulating radio signals so that they can carry information such as voice or data. Analogue cellular phones worked like a FM radio, the receiver and transmitter are tuned to the same frequency, and the voice transmitted is varied within a small band to create a pattern that the receiver can reconstruct. This limited the number of channels that can be used.

Digital communications technology was introduced with second generation (2G) mobile systems in the 1990s. In digital, the analogue voice signal is converted into binary code and transmitted as a series of on and off transmissions. The second generation systems are characterized by the provision of better quality voice services available to the mass market and the introduction of the cellular concept in which scarce radio resources can be used simultaneously by several mobile users.

Many of the early mobile communication systems utilised various standards, leading to incompatibilities across different countries and regions of the world. It wasn't until the introduction of GSM that a true global mobile standard emerged. This has driven a much tighter international cooperation around cellular technologies than for the earlier generations, resulting in economies of scale.

GSM is the most used mobile communication system today and has been a major breakthrough in the domain of mobile communications. GSM is currently the only digital technology that provides data services such as email, fax, internet browsing, and intranet/LAN wireless access, and it's also the only service that permits users to place a call from either North America or Europe.

This section provides important background to the various elements composing a typical GSM network and covers significant milestones in the evolution of its data transport capabilities, which will play an important role in the design of mobile cooperative environments. Milestones covered in this section include the introduction of General Packet Radio Service (GPRS) to 2G networks, enhancements brought by 3G data networks and the evolution to Internet Protocol data networks. This section concludes with an overview of GSM networks and their role in facilitating future mobile collaborative solutions.

3.3 The GSM Architecture

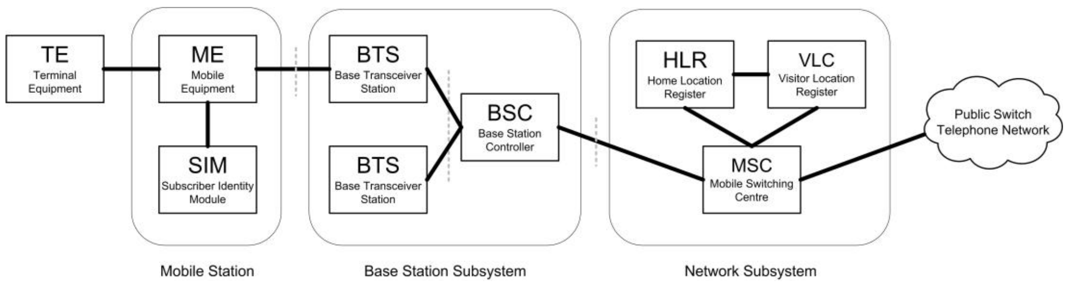

Figure 3.1: GSM Architecture.

The mobile GSM technology was first launched in Finland in 1991. Its growth has since exploded surpassing 100 million subscribers by 1999, to a billion by 2004 and over 3 billion in 2008 [GSMA]. Given the widespread adoption of GSM a basic understanding is a prerequisite to the deployment of any new cellular technology. The basic service of all GSM telephone networks is to provide a connection between two people, a caller and the called person. To provide this service, the network must be able to set up and maintain a call, which involves a number of tasks: identifying the called person, determining the location, routing the call, and ensuring that the connection is sustained as long as the conversation lasts.

In a fixed telephone network, providing and managing connections is a relatively easy process, because telephones are connected by wires to the network and their location is permanent from the network's point of view. In a mobile network, however, the establishment of a call is a far more complex task, as the wireless (radio) connection enables the users to move at their own free will, providing they stay within the network's service area. In practice, the network has to find solutions to three problems before it can even set up a call:

- Where is the subscriber?
- Who is the subscriber?
- What does the subscriber want?

In other words, the subscriber has to be located and identified to provide him/her with the requested services. In order to understand how GSM is able to serve the subscribers, it is necessary to identify the main interfaces, the subsystems and network elements in the GSM network, as well as their functions.

The main elements of the GSM architecture [3GPP-23.002] are shown in Figure 3.1. The GSM network is composed of three subsystems: the base station subsystem (BSS), the network subsystem (NSS) and the operation subsystem (OSS) that allows the administration of the mobile network. The main elements comprising this architecture and their roles are outlined in Appendix B.1.

3.3.1 Early Mobile 2G Data Networks (GPRS)

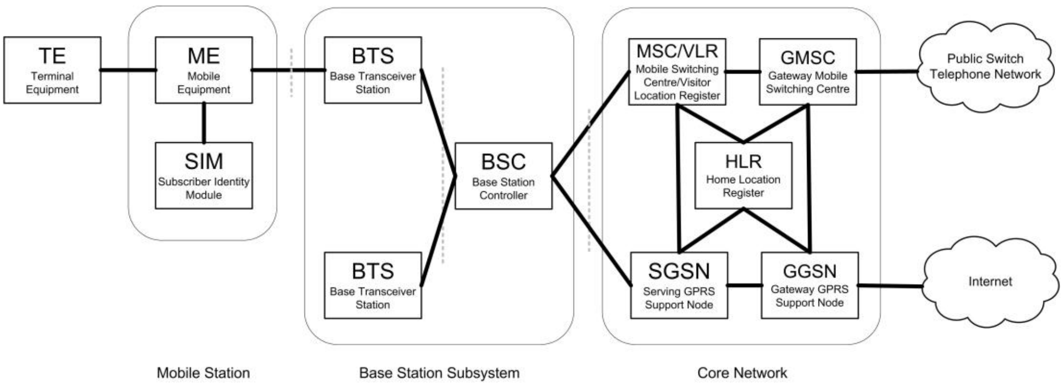

Figure 3.2: Second Generation GSM Architecture.

An important evolution of the GSM architecture is the introduction of the data networks. The primary data services introduced in 2G were text messaging (SMS) and circuit-switched data services enabling e-mail and other data applications. The peak data rates in 2G were initially 9.6 kbps. Higher data rates were introduced later in evolved 2G systems by assigning multiple time slots to a user and by modified coding schemes.

Packet data over cellular systems became a reality during the second half of the 1990s, with General Packet Radio Services (GPRS) introduced in GSM and packet data also added to other cellular technologies such as the Japanese PDC standard. These technologies are often referred to as 2.5G. The success of the wireless data service iMode in Japan gave a very clear indication of the potential for applications over packet data in mobile systems, in spite of the fairly low data rates supported at the time.

The infrastructure of 2G networks (see Figure 3.2) is in many ways very similar to that of the initial GSM architecture (see Figure 3.1), with two main additions in the form of the SGSN and GGSN added to the core network to provide internet connectivity.

The introduction of simple data access to cellular devices in 2G networks marked an important transition in the evolution of mobile cellular networks supporting voice only communication among connected clients, into a platform capable of supporting rich data exchange, e-mail downloads and web-surfing whilst on the go. The main elements comprising this architecture and their roles are outlined in Appendix B.2.

3.3.2 Existing Mobile 3G Data Networks (UMTS)

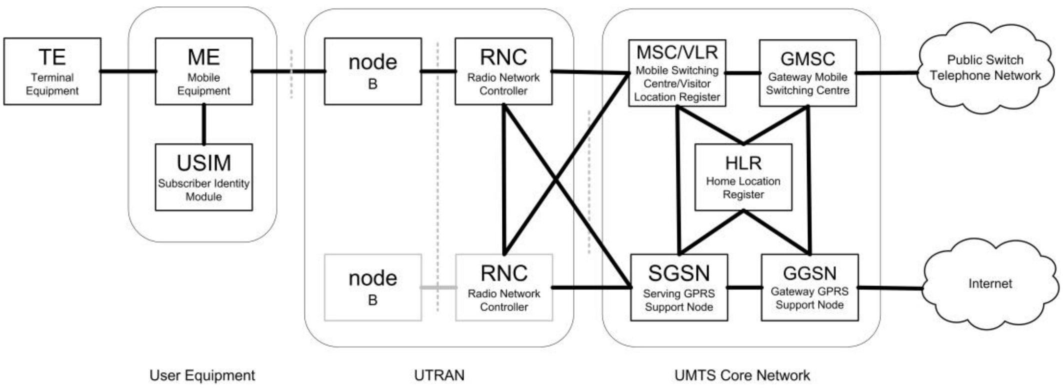

Figure 3.3: Third Generation GSM Architecture.

Universal Mobile Telecommunications System (UMTS) marked the third evolutionary milestone in the history of the mobile cellular landscape. 3G networks brought improved speech quality and advanced data and information services. The primary data services introduced in 3G were multimedia messaging (MMS), access to e-mail and the internet and the ability to send and receive full-motion video.

The peak data rates in 3G were extended up to 2Mbit/s. UMTS was designed as a true global system, comprising both terrestrial and satellite components and can be operated alongside GSM/GPRS networks.

3G systems use different frequency bands, so mobiles won't interfere with each other. The General Packet Radio System (GPRS) outlined previously was designed to facilitate the transition from phase 2 GSM networks to 3G UMTS networks. GPRS supplemented GSM networks by enabling packet switching and allowing direct access to external packet data networks.

The 2G architecture optimized the 'core network' for the transition to higher data rates. Therefore, the 2G architecture was an important prerequisite for the introduction of 3G UMTS networks. For 3G networks to achieve higher data rates, the base station subsystems of earlier 2G networks are enhanced in the form of Radio Network Controllers (RNC) that makes up a UTRAN network, between the user equipment and the UMTS core network (see Figure 3.3). The main elements comprising this architecture and their roles are outlined in Appendix B.3.

3.3.3 Next Generation Mobile IP-Data Networks (IMS)

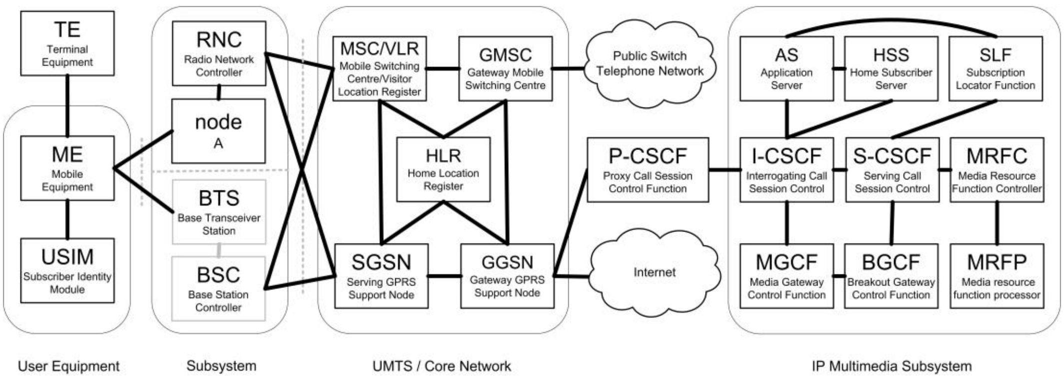

Figure 3.4: IMS (IP Multimedia Subsystem) Architecture.

The Internet Protocol Multimedia Subsystem (IMS) [Camarillo and García-Martín 2004] is an architectural framework for delivering the next-generation internet protocol (IP) voice and multimedia communications across mobile networks. It was originally designed by the wireless standards body 3rd Generation Partnership Project (3GPP), and is part of the vision for evolving mobile networks beyond GSM.

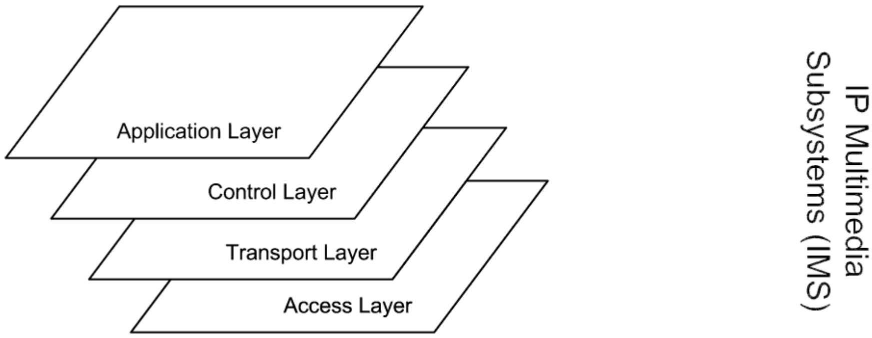

Figure 3.5: IMS (IP Multimedia Subsystem) Layers.

Unlike earlier 2G/3G networks that marked incremental updates to the data capabilities and bandwidth provided to cellular devices, IMS is designed to fill the gap between the existing traditional telecommunications technology and internet technology, enabling the convergence of data, speech and mobile network technology over an IP-based infrastructure that increased bandwidth alone will not provide.

IMS was specifically architected to enable and enhance real time, multimedia mobile services such as rich voice services, video telephony, messaging, conferencing, and push services. IMS enables these user-to-user communication services via a number of key mechanisms including session negotiation and management, Quality of Service (QoS) and mobility management over rich IP based protocols.

IMS is specified as an incremental add-on to existing mobile 2G (see Figure 3.2), 3G (see Figure 3.3), wireless and fixed networks rather than a radical replacement. In that sense IMS shares many of the existing technologies throughout its Subsystems and Core Network layers (see Figure 3.4). IMS integrates at the GGSN gateway node enabling direct terminal connections using Internet Protocol (IP) over IPv6/IPv4 and Session Initiation Protocol (SIP) [Handley *et al.* 1999]. The main elements comprising this architecture and their roles are outlined in Appendix B.4.

IMS differs from previous network architectures in that it provides an open framework designed on the success of the Internet and the IP-based services to deliver point to point connections. IMS uses the SIP protocol (Session Initiation Protocol) for multimedia session negotiation and session management. IMS is essentially a mobile SIP network designed to support this functionality, where IMS provides routing, network location, and addressing facilities.

IMS systems are based on the four layer architecture (see Figure 3.5). The bottom-most IMS access layer works with legacy circuit-switched networks along with the latest cable, packet and wireless networks, allowing IMS to function across access technologies. IMS also specifies an applications layer that supports a broad range of voice, video and multimedia applications. The final two layers: control and transport provide the signalling and connectivity between users and their applications.

3.4 Chapter Summary

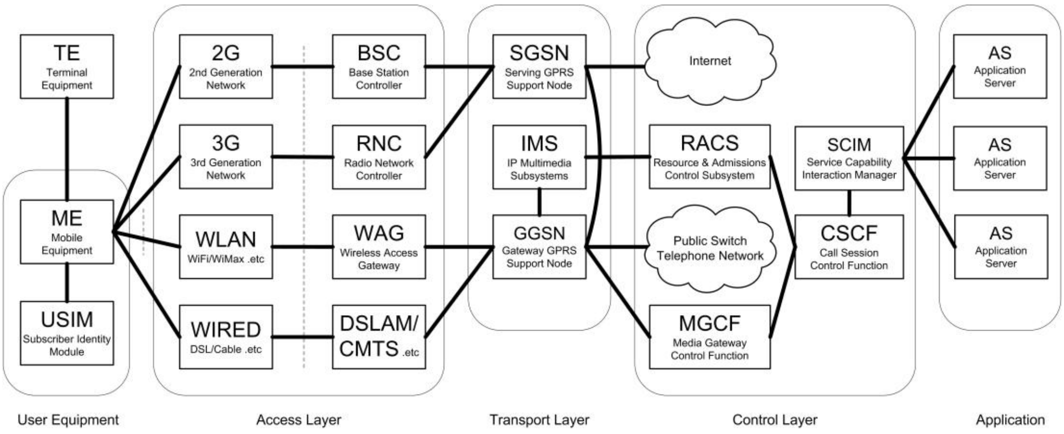

Figure 3.6: Network Agnostic Architecture.

This chapter has thus far presented a detailed description of the GSM architecture, its global presence providing economies of scale to mobile operators and its current infrastructure and capabilities which are important for understanding and framing the work that is presented in the rest of this thesis. Here we summarise those capabilities and limitations as they relate to rich mobile media exchange.

- 2G: Although 2G networks paved the way for data transfer to mobile devices, there were many inherent limitations in its early architecture. Specifically the incorporation of device 'classes' directly influenced the way in which mobile device stations (MSs) maintained voice and data connectivity. As a cost reduction measure, the majority of mobile operators and device manufacturers opted to sell 'Class B' rather than 'Class A' GPRS devices. Class B devices were limited to serve up voice or data to end-users but not both at the same time, which limits the communication functionality of 2G networks to a single communication channel. Additionally, slow data speeds, restricted services and inadequate software further limited communication functionality throughout early 2G networks.

OSI	TCP/IP and Related Protocols		
Application	File transfer	Electronic mail	Terminal emulation
Presentation / Session	File transfer protocol (FTP)	Simple mail transfer protocol (SMTP)	Telnet protocol
Transport	Transmission control protocol (TCP)		User datagram protocol (UDP)
Network	Address resolution protocol (ARP)	Internet protocol (IP)	Internet control message protocol (ICMP)
Data link	Network interface cards: CSMA/CD (Ethernet), Token Ring, ARCNET, StarLan		
Physical	Transmission media: Wire pair, fiber optics, coaxial cable, radio		

Figure 3.7: The TCP/IP and associated protocol OSI layers.

Early 2G data services provided a giant leap forward in the ideas and visions that would shape future mobile services, but were limited both in capabilities and infrastructure. Despite these limitations, simple mobile collaborative environments would have still been possible across 2G networks, albeit restricted to a single communications channel and limited in their real time interaction capabilities to the semi-real time exchange of small data packets.

- 3G: In contrast to earlier 2G and 2.5G networks, 3G networks presented the first evolutionary step towards the integration of mobile data and voice communication infrastructures, enabling new avenues of communication. The main advantage of 3G networks lies in its simultaneous data and voice capabilities, unlike earlier 2G systems (see section 3.3.1). 3G enables users to talk on the phone (voice traffic) while simultaneously surfing the web, checking email or using applications such as Maps (data traffic).

  However, to enable mobile-to-mobile sessions, 3G networks would require the means to connect multiple participants. Session Initiation Protocol (SIP) [Handley, et al. 1999] is one such IETF signalling mechanism used in the establishment, modification and termination of networked sessions between fixed network devices. Though SIP works over fixed networks, it currently provides no support for ensuring delivery of data packets between mobile participants that roam between different sub-networks, or any support for determining the location of a mobile host at session set-up time. And because 3G networks borrow heavily from earlier 2G GSM architectural designs (see section 3.3.2), it too lacks the IP addressability needed to allow SIP's session management protocols to operate, establish the required connections and make use of UDP/TCP protocols to route data back and forth between connected devices.

- IMS: The IMS application layers are a huge departure from traditional GSM architectures that consist of various proprietary protocols and silo applications, e.g. MMS that varied across different operators and networks. This unified application layer introduces transparency to previously ungoverned operator network filtering and firewall restrictions, ensuring applications can receive and re-direct data packets along dynamic paths to their final destinations.

  The IMS upper layer applications approach is borrowed from the traditional networking model, and would be familiar to anyone who has come across the seven layer OSI model (see Figure 3.7). This separation of software, hardware and underlying transport mechanisms reduces the reliance on a specific set of hardware or networking standards, allowing for the creation of network agnostic application services out of the box.

Of the GSM networks presented, IMS offers the most potential to facilitate mobile exchange architectures (MEAs). However, despite the many advantages IMS may one day deliver, it currently stands in sharp contrast to the commercially available 2G/3G cellular networks and still remains a far-away prototype that's yet to achieve commercial availability, currently limiting IMS's capabilities and applicability to reduced lab based scenarios. Though this might change in the future, IMS's fluctuating roadmap has already resulted in many sceptics of the technology [Waclawsky 2005] and only time will tell whether IMS will truly live up to its goals and evolve from a mere prototype to a next generation mobile network.

Therefore it would be more beneficial to facilitate mobile media exchange over existing 2G/3G networks. 2G networks are however limited to a single communications channel and restricted bandwidth that would also limit their capabilities to support such features. By a process of elimination this leaves 3G networks as the only remaining cellular candidate to facilitate rich mobile media exchange. However, unlike traditional fixed networks that support TCP/IP communication, in 3G networks there's no support for shared sessions or even direct mobile to mobile communication outside of voice only connectivity.

Taking into account the lack of SIP capabilities in 2G/3G mobile networks and that it's common practice for mobile operators to heavily utilise firewall systems and ingress filtering mechanisms to further prevent inbound data connections to mobile devices, the challenge then becomes how to enable SIP functionality over current IP-less 3G cellular networks. In the next chapter we will look at how such an SIP layer can be incorporated into the creation of a mobile exchange architecture that can work across existing 3G networks.

Chapter 4.

Mobile Exchange Architecture

"It is the framework which changes with each new technology and not just the picture within the frame" Marshall McLuhan

4.1 Introduction

Our previous chapters have examined the need for mobile media exchange solutions to assist with our ever increasing nomadic lifestyles and have sought insight from the existing literature and state of the art to understand the current limitations and requirements to providing such services across the mobile domain. In this chapter, as part of our efforts to further understand how we can better design and build systems to support digital media exchange across 3G mobile devices, we report the development of an end-to-end mobile exchange architecture to create the foundation for future work that will allow users to communicate and exchange digital media across remote and co-located mobile cellular devices.

This chapter describes the design of the mobile exchange architecture [Yousef and O'Neill 2007, Yousef and O'Neill 2008] to support the sharing of different forms of digital media data types between mobile devices. The chapter builds upon the GSM networks outlined in the previous chapter and provides technical insight into the implementation of a mobile exchange architecture that is vital to enabling rich mobile media exchange capabilities.

4.2 Mobile Exchange Architecture

The mobile exchange architecture (MEA) is a set of contributing technologies targeted specifically at resource restricted mobile phone based cellular devices. The architecture allows users to engage in digital media sharing during a mobile phone call, allowing the utilisation of the voice channel. It uses a 3G internet connection to exchange data between participants and plain old telephone service (POTS) to exchange voice data.

The architecture is designed to achieve these goals and overcome the limitations of existing mobile cellular networks. The mobile exchange architecture presented here is device, network and operator independent. This means that the MEA will work across most mobile phones and allow users to freely switch between operators that provide cheaper services or better coverage.

The mobile exchange architecture is designed to cater to real-time applications (e.g. games) that require small amounts of data to be updated relatively frequently with low delay, and push-based applications that need to exchange large amounts of data (e.g. media packages) with minimum delay, and applications supporting both. As such the mobile exchange architecture supports the mechanic of collaborations [Gutwin and Greenberg 2000], through the following requirements:

> *[f1] Communication: To establish local and remote sessions, the underlying infrastructure provides the ability to find other users in the network and then to establish a session with that user.*
>
> *[f2] Coordination: To enable real time interactions and the creation of shared interaction spaces among all connected participants.*
>
> *[f3] Transfer: Supporting data exchange between participants, encompassing the transfer and distribution of all media between participants. Such media may include audio, video and messages.*

To realize these goals, we developed a complete bespoke person-to-person mobile exchange architecture, designed from the ground up to work over existing GSM 3G and future networks. The following section outlines the components of this MEA, its functionality and the operation of the underlying protocols.

4.3 Architecture Overview

The mobile exchange architecture consists of a number of components that integrate with existing GSM communication systems. Figure 4.1 provides an overview of these components, with a more detailed overview provided in Figure 4.4.

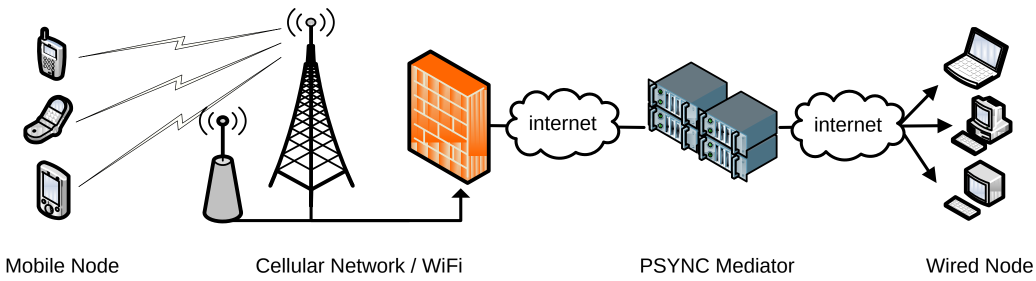

Figure 4.1: Mobile exchange architectural overview.

- Mobile/Wired Node: Consist of devices running a highly optimized multi-threaded layer of Push-Sync (PSYNC) protocols wrapped in a custom application software interface. The application software is separated from the PSYNC protocols by a set of APIs enabling different applications to be developed for different consumer and business scenarios that benefit from the underling packet transmission, compression and encryption methods encompassed in the PSYNC layers.

- The client based software automatically establishes a connection to the PSYNC Mediator upon initiation to report status, receive data and join or establish session requests. Based on the type of application used and security level, the client software will connect to the PSYNC Mediator using either HTTP or secure HTTPS protocols for added privacy.

- PSYNC Mediator: The Push-Sync (PSYNC) Mediator lies at the heart of the service and is responsible for registration, authentication, routing of data between connected clients and the maintenance of all active sessions among connected clients.

- The PSYNC Mediator consists of four modular components: the session manager, consumption manager, upload manager and state manager. This division of labour ensures failure resilience, scaling and load balancing to support an arbitrary number of connected clients across multiple sessions.

- The PSYNC Mediator constantly monitors all active clients and any associated sessions. It delivers required data and notifications to connected peers, ensuring real time communication, stability and data integrity. The PSYNC Mediator can support multiple clients (mobile and wired) connected to the same session, multiple sessions or distributed across separate sessions, maintaining state information across all connected clients.

- Network Interface: PSYNC services are network agnostic, supporting Code Division Access (CDMA), General Packet Radio Service (GPRS), 1x Evolution-Data Optimized (1xEV-DO), Universal Mobile Telecommunications System (UMTS), Wi-Fi (IEEE 802.11) and WiMax (IEEE 802.16), in addition to existing cellular and wireless networks as well as future networks supporting web access and voice communication.

4.4 Extensibility

The mobile exchange architecture is built on an extensible infrastructure similar to IMS and the seven layer OSI model (see Figure 3.5, 3.7), to enable a rich set of applications to be deployed upon a single extensible robust mobile exchange architecture.

The MEA protocol stack is shown in Figure 4.2 opposite the Open Systems Interconnect (OSI) standard reference model. The OSI model provides the basis for connecting open systems for distributed applications and is the basis of all IP communications. To meet the requirements [f1-3], it is desirable to ensure maximum independence among the various software and hardware elements of the system to facilitate intercommunication among disparate elements; and to eliminate the “ripple effect” when there is a modification to one software element that may affect other elements.

In the OSI model the lowest layers include the physical connection and the data link layer. Examples are a local area network, a dial-up link, or a wireless network. This link layer can be quite complicated (including different message formats and control mechanisms), but it is simply used to transfer content or payload from one link endpoint to another. Built on top of this layer are additional protocols, such as TCP and IP, used to route payload from one network node to another in a network that can be extremely large (e.g. the Internet).

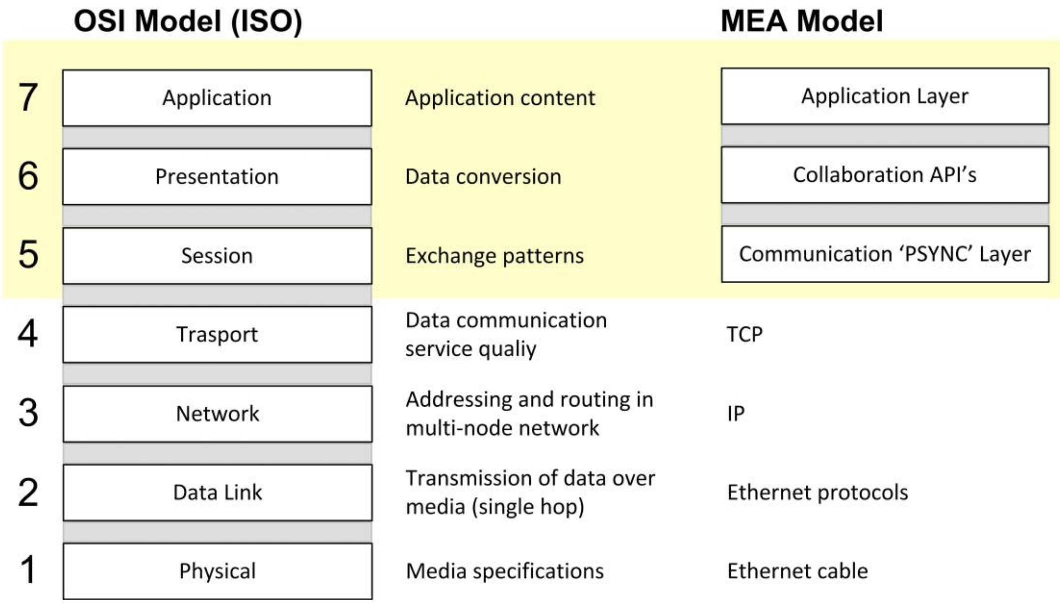

Figure 4.2: OSI seven layer model and MEA model.

As a web-based mobile protocol, the MEA is designed to allow mobile nodes to communicate with one another. It is transmitted using protocols (5, 6 and 7) higher in the protocol stack.

However, this OSI mapping is a highly simplified view of what actually takes place in networking environments today. In reality, nominally lower-layer protocols are often layered on top of nominally higher-layer protocols. To take an example, suppose we are looking at web traffic. The typical protocol stack would be, from the bottom up: Ethernet / IP / TCP / HTTP. This is the OSI model that textbooks describe for IP networks, in simplified form. The physical layer is at the very bottom, but goes without mention, and there is no session layer or presentation layer between TCP and HTTP.

Although many systems rely on such simple four layer architectures that follow the OSI model, in reality many architectures are far more complex. In 3G operators' networks for instance, web traffic looks like this: Ethernet / IP / UDP / GTP / IP / TCP / HTTP. The application is the same, but the transport network is different because the operator tunnels traffic over the GPRS Tunneling Protocol (GTP). Notice that IP appears twice in this stack: once directly on top of Ethernet, where the OSI model says it belongs, but once higher up than UDP.

In this case the OSI model takes on the form of a directed graph, where each node in the graph represents a protocol and each directed link between nodes would allow a second protocol to be layered on top of the first. Graph layering introduces added complexity compared to linear stacks, though a combination of both helps the mobile exchange architecture to decompose the problem into more manageable parts and provide a standard architecture to enable collaboration tasks.

4.5 Layered Architecture

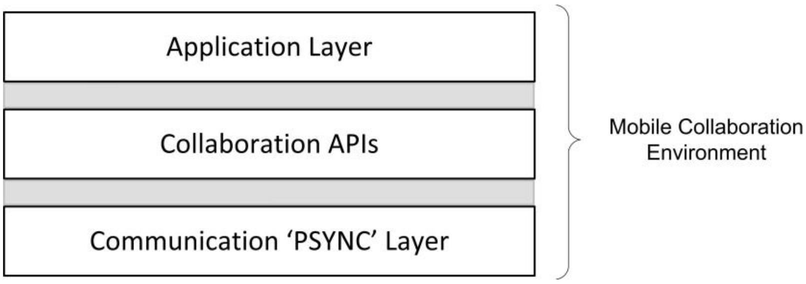

Figure 4.3: MEA extensible architecture.

The MEA's main modules are composed of linear layers using the lowest protocols (5, 6 and 7) of the OSI protocol stack (see Figure 4.3), with the interconnections between layers on the mobile node taking on a graph representation (see Figure 4.4). Details of the layered architectures are described below:

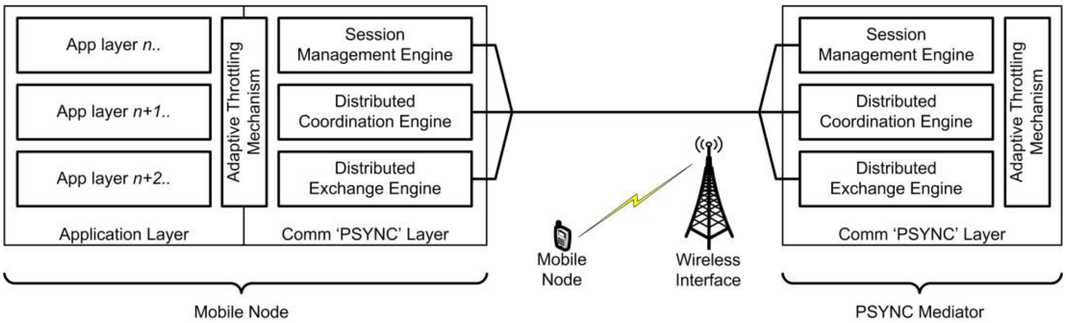

Figure 4.4: MEA detailed architectural overview.

- Application Layer: The application layer consists of solutions designed to make use of the mobile exchange architecture and makes up the lowest layer of the exchange architecture (OSI layer 1). An important role of the application layer, especially in the MEA model, is to allow for clear separation between solutions and application logic built on top of the MEA and the underlying routines, procedures and protocols required to establish mobile sessions and maintain active data connections between mobile nodes.

This approach enables a slew of new applications to be created that make use of the MEA’s cooperative capabilities, without requiring in-depth knowledge of mobile communication protocols, file transfer coding schemes and session management procedures that are handled by the upper layers of the MEA. This facilitates modular interfaces to incorporate new services and a set of application protocols that allow the creation of solutions that can utilise the underlying architecture.

- Exchange APIs: The application programming interfaces (API) layer provides the means for application processes to access the MEA and to ensure a common data representation is maintained. The API layer provides the link between the application layer comprising of solutions that want to access and make use of distributed mobile nodes and lower layer communication protocols that facilitate the communication and connectivity that take place between distributed mobile nodes. This enables intercommunication among disparate elements, that’s scalable to support multiple devices connecting simultaneously to one another, whilst providing sufficient quality-of-service and fault tolerance in spite of intermittent mobile connections

- Communication ‘PSYNC’ Layer: The push-sync mediator occupies the core of the mobile exchange architecture, facilitating session establishment and data control between mobile nodes in the system. The MEA messages are typically conveyed using HTTP or HTTPS (i.e. HTTP secured by SSL/TLS). However, they can also be conveyed using other protocols, such as e-mail or Short Message Service (SMS) text messaging. The mobile exchange architectures ‘PSYNC’ communication specification defines how these messages are exchanged and describes in detail how the two should work together and offer an interoperable, agnostic, rich communication experience.

In the following sub-sections we look at each of these layers individually starting with the highest layer: the Communication ‘PSYNC’ Layer. Here we provide a detailed overview of its key components, communication protocols and functionality required to establish group sessions, facilitate interaction, and enable data exchange between mobile nodes. The next layer covered is the collaboration APIs that shield application developers from the complex inner workings of the PSYNC layer through elevated functions that provide unified easy access to the rich media exchange functionality of the system. The final section covers the highest layer of the MEA in which the applications reside, “the Application layer”, and provides an overview of recommended elements for rendering visual components between connected nodes.

4.5.1 Communication ‘Push-Sync’ Layer

The Push-Sync mediator makes up the heart of the mobile exchange architecture, consisting of four modular components: a session management engine, a distributed coordination engine, a distributed exchange engine and a session management engine. In addition to these core modules an underlying adaptive throttling mechanism is employed throughout all layers of the push-sync mediator to ensure optimum response times (see Figure 4.7).

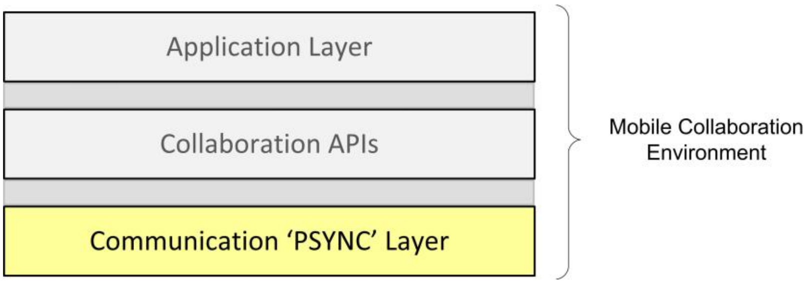

Figure 4.5: Mobile Exchange Server architectural detail.

The communication ‘PSYNC’ layer makes up the highest of the OSI layers (Layer 5, see Figure 4.5, 4.2). It provides the establishment and control of the message packets between mobile nodes and is the only layer that’s shared across the mobile node and push-sync mediator (see Figure 4.6).

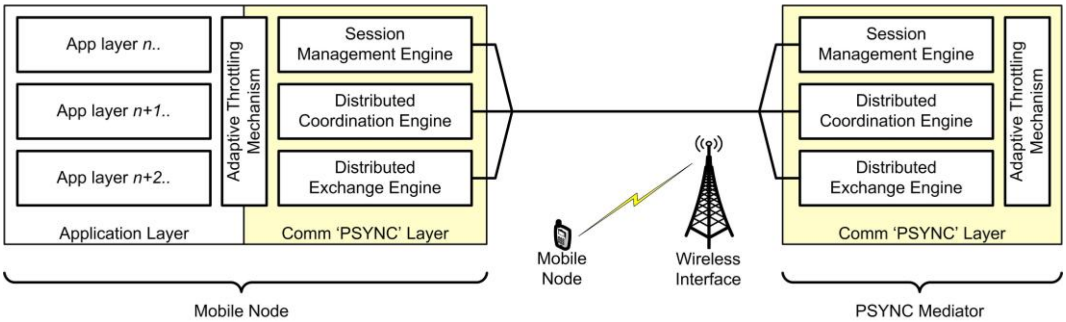

Figure 4.6: MEA detailed architectural overview,
with highlighted push-sync layer.

In order to perform its role, the push-sync layer is made of four core components as outlined below. More in-depth details are provided on each of these components in the next section; see Figure 4.7:

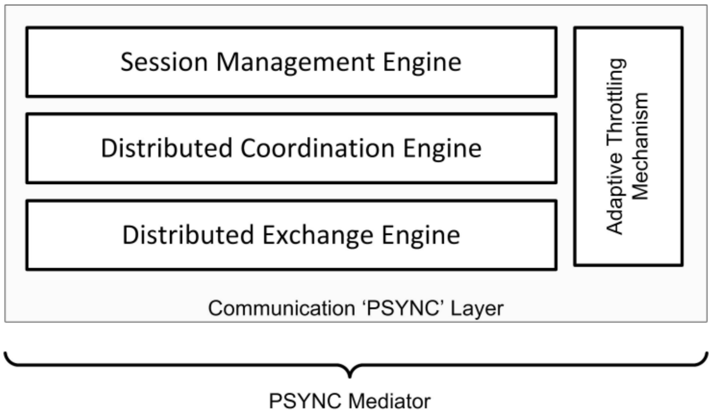

Figure 4.7: Push-Sync Mediator modules.

- Session Management Engine: The session management engine (S|ME) facilitates the signalling protocol used to establish communication between mobile nodes and enables the creation, modification and termination of multicast sessions.

- Distributed Coordination Engine: The distributed coordination engine (D|CE) is responsible for the maintenance of a shared visual space, real time monitoring of session based state changes, ownership of resources and the distribution of state updates to connected nodes.

- Distributed Exchange Engine: The distributed engine (D|EE) is responsible for enabling the exchange of resources among connected nodes and monitoring the consumption of such resources.

- Adaptive Throttling Mechanism: Adaptive throttling is a client side technology responsible for ensuring a minimal level of performance and responsiveness across client nodes during an active session.

4.5.1.1 Session Management Engine

The session management engine (S|ME) is responsible for coordinating presence, initiating a connection between two cooperative nodes in the network, the addition of supplementary nodes to a shared session and the management and termination of all session based connections. The session initiation process is outlined in Figure 4.8 and discussed further in 4.5.1.1.2.

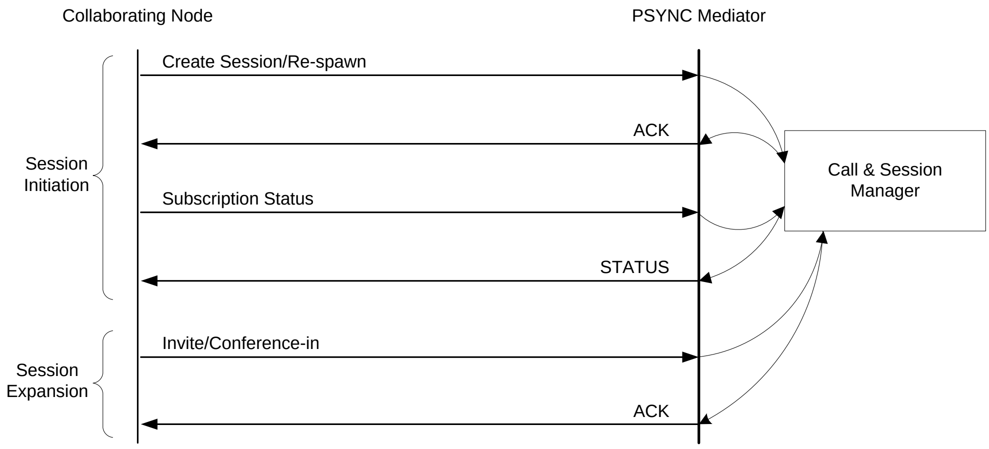

Figure 4.8: Session creation process overview diagram, see protocols 4.5.1.1.2-6 for additional information.

The process of establishing a shared session is initiated client side on the user's device. The process has been specifically designed to resemble the familiar process of creating a voice call in which the user selects a contact, dials the number and initiates a conversation.

4.5.1.1.1 Seamless Session Creation

A shared session differs significantly to mobile video conferencing [O'Hara *et al.* 2006] in a number of key usability areas. The current process of mobile video-conferencing requires the user to pre-emptively engage in a video-conferencing call or a voice call prior to dialling the intended recipient.

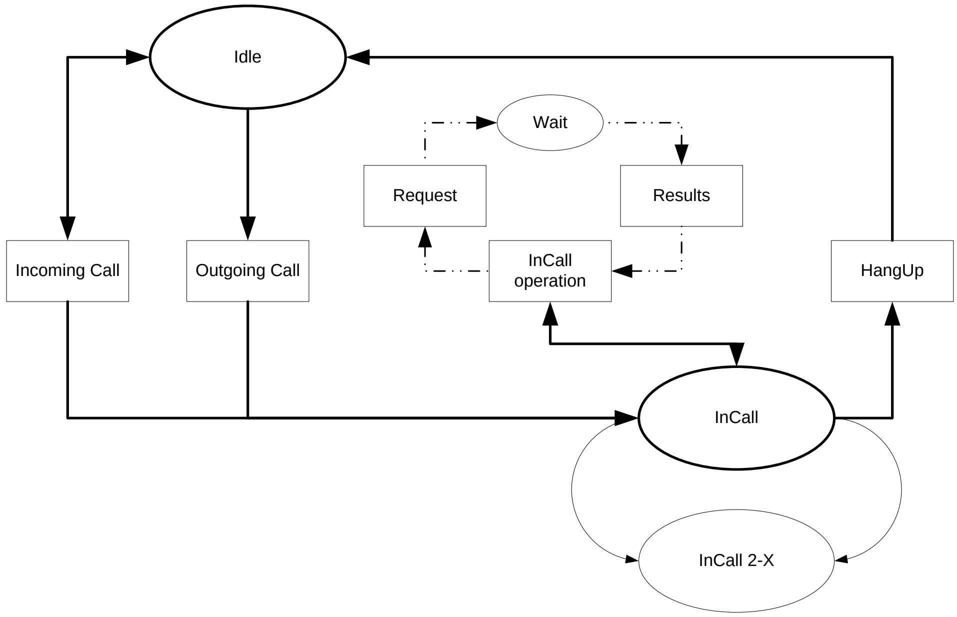

Figure 4.9: Stages of a call lifecycle.

This has two major drawbacks; first, it reduces the opportunity for spontaneous interactions: A user initiating the voice call cannot seamlessly switch to video conferencing without hanging up and redialling. Secondly, a user initiated video-conference call can't switch over to a voice only call when video is no longer required.

There has been ample research into the advantages and disadvantages of video as presence compared to video as data [Kraut, et al. 2002, Whittaker and O'Conaill 1997], however a more important focus of the session initiation process was to allow for spontaneous sharing [Cooley 2005] as exists in real life. For that to occur, seamless switching between conferencing (Voice + Interaction + Data) and non-conferencing (Voice only) needs to be supported.

Our process of establishing a session has therefore been designed to occur before the call (idle), during the call (in-call) and to persist after the call (hang-up) encompassing all major stages of the call's life cycle; see figure 4.9.

4.5.1.1.2 Session Initiation Protocols

Communications between the Connected Node (CN) and the Push-Sync Mediator (PM) are covered in the dialogue based representation below, providing insight into the information exchanged between both parties and their roles in the session initiation process. Only the dialogue between a single connected client and the Push-Sync mediator is highlighted, however the process applies to all connected clients. In circumstances where the presence of additional connected session nodes affect the logic of the operation being discussed (CN~) is used to represent these changes.

4.5.1.1.3 Session initiation 'dialling' process

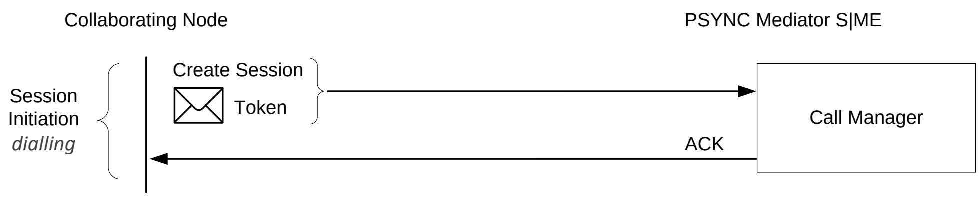

Figure 4.10: Session initiation 'dialling' process.

CN: The initiating user starts by selecting the intended recipient the user wishes to engage with in a shared session from the phone's built in address book or contact list. This is similar to the process of creating a voice call. The user then initiates the connection which commences the 'dialling' process. The dialling process identifies both parties and creates a session request by transmitting a token to the PM's call manager, see Figure 4.10.

PM: The token is received by the call manager, checked to insure correct formatting, header checksums and recipient validity before returning an acknowledgement of delivery to the initiating node. The received token contains a number of user attributes that serves to identify both parties (the source and target) of the shared session. The attributes pertain to two unique key values the first relevant to the user: which defaults to the users preferred phone number and the latter is specific to the connected device: which in the cellular device scenario defaults to the cellular devices unique identifier IMEI (International Mobile Equipment Identity) number. In a PC scenario the unique identifier can be configured to use the MAC (Media Access Control) address or similar unique identifying attribute.

These attributes ensure subscribers maintain a universal accessible identifier at the PSYNC Mediator that is globally addressable at a user and device level. This allows addressability over IP-less 3G cellular networks and across firewall restricted connections.

The dual addressability also serves an important role in ensuring the system is scalable to support a multitude of devices (mobiles, laptops, PCs .etc) that a user may wish to engage through in the future and that the system can target the recipient at both a device level and a broader user level independent of the user's device.

4.5.1.1.4 Session initiation 'ringing' process

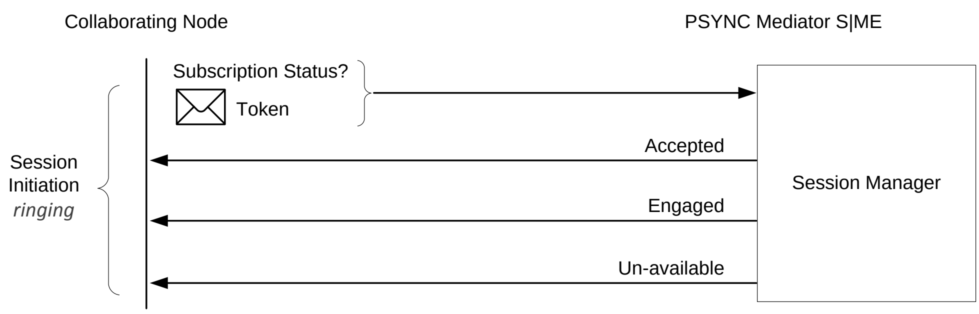

Figure 4.11: Session initiation 'ringing' process.

CN: Upon receiving the PM's acknowledgment of message delivery the connected node enters 'ringing' stage, in which it enters a blocking mode and waits for the newly created session to be accepted by the remote user, see figure 4.11.

PM: As soon as the CN enters ringing mode, the call manager automatically hands over operations to the session manager, freeing up the call manager to focus on validating new incoming session creation requests. Sessions are managed using a subscription system in which one or more nodes can join a session by subscribing to its synchronisation queue.

The role of the session manager is to act as a broker allowing users to subscribe to new/existing sessions, keep track of session subscription and manage associated users. In the ringing process, the role of the call manager is to broker a new session subscription contract between connecting parties. This is achieved by forwarding the session requests to all intended participants and returning one of three responses to the initiating node:

- Accepted: This notifies both parties that the session has been accepted, that both parties are now subscribed to the session and are ready to communicate.

- Engaged: This status identifies the target node as being aware of the incoming session request but is currently engaged in another shared session or pre-occupied with another task and does not wish to participate in the new session.

- Unavailable: Differs from engaged in that unavailable denotes that the target user is currently inaccessible or out of range. This status is more specific to mobile clients, which are more susceptible to signal loss and network outages.

CN: The session subscription status request is returned to the connected node. When 'engaged' or 'unavailable' is received the connected node discontinues the session request and notifies the initiating user. The 'accepted' status session request response differs from the previous two status requests in that the accepted request contains both a status response 'accepted' and a verified session invitation token, see Figure 4.12.

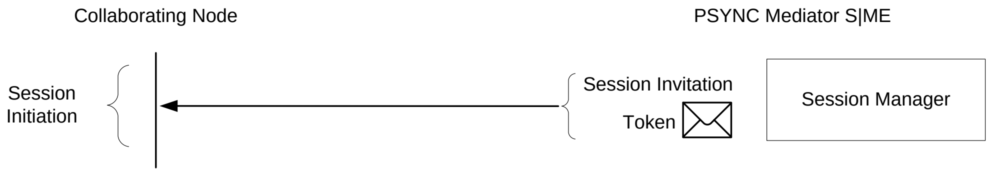

Figure 4.12: Session invitation token.

PM: The verified session initiation token is returned to the connected node with an 'accepted' session request status. The session invitation token contains the session information and verification codes required to establish a data-channel between both nodes to converse and exchange data.

CN: Upon receiving a session invitation token, the session initiation process ends and both nodes enter into a shared session

4.5.1.1.5 Session expansion process

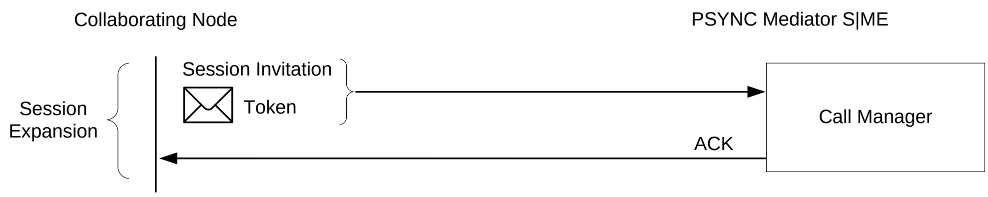

Figure 4.13: Session expansion process.

CN~: During an active session new users can be invited to participate in the already active session by issuing a session invitation token to another participant from the user's address book or contact list, see Figure 4.13. This process differs from that of a newly created session between two participants in that a non blocking 'ringing' process is utilised to allow the active session to continue without acknowledgement from the inviting party. The use of a non blocking 'ringing' process allows the current ongoing shared session to commence as usual without any interruptions (i.e. participants don't need to wait for the new party to join before resuming the session). The invited recipient upon accepting the session invitation will be sent the latest state update of the active session, allowing the participant to catch-up with the latest session information.

PM: The session invitation process is similar to that of session creation, in which the call manager hands over verified requests to the session manager for acceptance status confirmation and distribution of invitation codes to authorised nodes. In addition the session expansion invitation packets contain additional information to inform new nodes on the number of active clients and latest session information.

4.5.1.1.6 Session terminating process

Figure 4.14: Session contraction process.

CN~: During an active session any user can join or leave a session at will, this differs from unplanned disconnects caused by mobile networks in which the participating nodes are subject to a grace period in which the client based software will attempt to reconnect and catch-up with the latest session information.

The process of terminating a session can occur in two situations. The first is linked to the client that initiated the connection. Initiating clients can transmit an ‘end session’ token to notify all active users connected to the session that the session is terminating, see Figure 4.14.

The other scenario in which an ‘end session’ is transmitted occurs automatically by the PSYNC manager when the number of clients in the system drops below an acceptable threshold (currently set to 2 active users), due to nodes leaving the session (clean disconnect) or when clients drop from the session (unplanned disconnects) caused by signal loss and a suitable time-out being reached.

PM: Upon receiving the end session token, the PSYNC manager ceases updates to the session state and informs all active clients that the session in which they were connected has been terminated. The termination of any session involves the session manager un-subscribing the connected nodes from the session update stream and returning them to their previous state.

4.5.1.2 Distributed Coordination Engine

The distributed coordination engine (D|CE) is responsible for the maintenance of a shared visual space, real time monitoring of session based state changes, ownership of resources and the distribution of state updates to connected nodes. The state management process is outlined in Figure 4.15 and discussed further in 4.5.1.2.2.

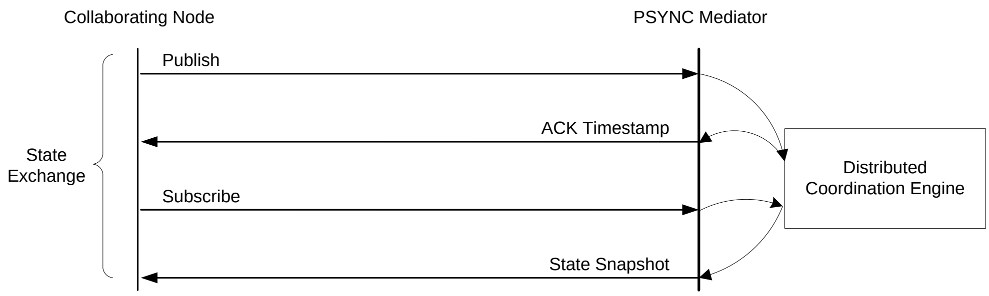

Figure 4.15: Distributed coordination process overview diagram, see protocols 4.5.1.2.2-4 for addition information.

In the previous section we discussed the session management engine and its role in the session creation process. The distributed coordination engine is initiated immediately after the session initiation process has completed, and is responsible for the ongoing maintenance of all active sessions until their termination.

4.5.1.2.1 Exchanging 'state' information

In order to enable mobile media exchange, two primary forms of information need to be exchanged between mobile clients: smaller control packets that manage the distributed nodes and larger media packets, e.g. files, videos and images that are exchanged between connected nodes (see Figure 4.16). In a typical networking scenario it would suffice to propagate each control packet across the network, e.g. pan left, pan right, zoom in, etc. However, mobile clients are more susceptible to disruptions in connectivity, which can lead to packet loss and render some or all remote clients out of sync.

To overcome this problem, the distributed coordination engine was adapted to exchange "state" information rather than "event" data. State information consists of significant attributes pertaining to active components, e.g. the displayed components' dimensions and x,y co-ordinates, etc. This allows the system to be far more resilient to packet loss and out-of-order events.

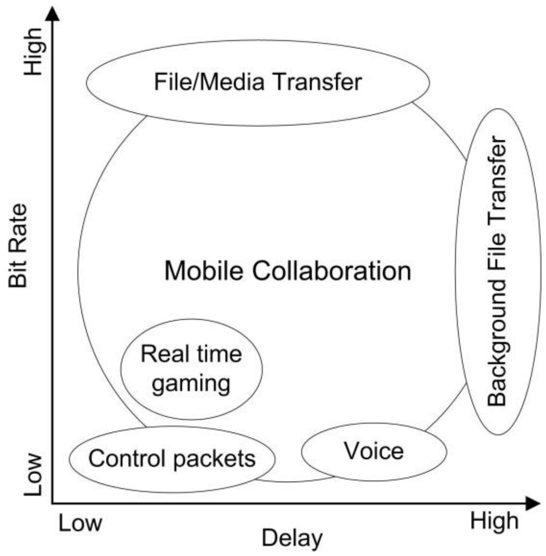

Figure 4.16: Data types comparison bit-rate/delay.

The drawback to this approach is that in comparison to single event transmission, state transmission packets are larger, incurring additional data overhead. However, by adopting state transmission, the need for delivery acknowledgment packets can be eliminated, as lost packets can be discarded in favour of new incoming data carrying the latest state information. Avoiding the associated overhead of checking whether every packet actually arrives in an interactive conferencing system is made even more important when slower mechanisms such as HTTP requests are required to traverse firewalls.

4.5.1.2.2 State Coordination Protocols

Adopting the same notations, communications between the Connected Node (CN) and the Push-Sync Mediator (PM) are covered in the dialogue based representation below, providing insight into the information exchanged between both parties and their roles in the session initiation process. Only the dialogue between a single connected client and the Push-Sync mediator is highlighted, however the process applies to all connected clients. Adopting the same symbols used in the previous section (CN~) denotes circumstances where the presence of additional connected session nodes affects the logic of the operation being discussed.

4.5.1.2.3 State exchange ‘publish’ process

Figure 4.17: State update process.

CN~: Nodes in a shared session maintain both an ‘active’ and ‘passive’ status. In passive state nodes update their visual space to reflect changes made by other nodes during the shared session. In the active state nodes participate and contribute (publish) changes made to the shared session, see Figure 4.17.

CN: A node primarily becomes active in response to user input e.g. the pressing of a key or the use of a menu function which affects the shared space. The results of these actions are packaged into a state publisher token with the session identifier and transmitted to the state manager.

PM: The token is received by the state manager, checked to insure correct formatting, header checksums and recipient validity prior to distributing the update to all relevant connected nodes in the shared session.

4.5.1.2.4 State exchange 'subscribe' process

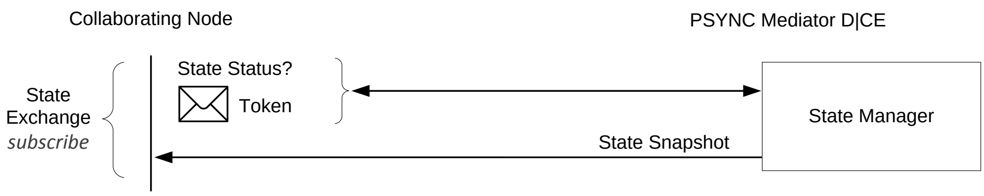

Figure 4.18: State request process.

CN~: All nodes are automatically subscribed to the session state manager during the session initiation process (see previous section).

PM: To maintain a shared space the state manager can issue state update requests to connected nodes. Each node in the shared session is tuned to a state synchronisation clock (see Figure 4.18). On each beat of the clock client states are synchronised to the shared session state.

In a cellular network over 180 state update requests can be issued by the state manager every minute, approximately one update every 300 milliseconds based on network coverage and signal strength. This enables our system to maintain a highly dynamic shared space between connected devices, for multiple devices to simultaneously tune to a single state synchronisation clock and for new clients to join an existing session by subscribing to the session's existing state synchronisation clock.

Before a state update request is issued to the connected node the state manager compares the global session state queue to the node's state queue. If the state of the connected node differs from the global session state, an update 'state snapshot' is transmitted to the connected node, see Figure 4.18.

CN: The connected node receives the state update and refreshes the local shared space to mimic that of the global shared space. Because constant user interface and state updates can drastically affect node performance if not governed correctly, user interface updates in addition to incoming state updates are governed by a throttling process (see Adaptive Throttling Mechanism 4.5.1.4) to manage this process.

4.5.1.2.5 Coping with 'jitter' effects

Jitter is a common side effect to any state based synchronisation approach, in which roundtrip network delays can extenuate subtle differences between local state information and that of the global state. This can be observed in the following scenario:

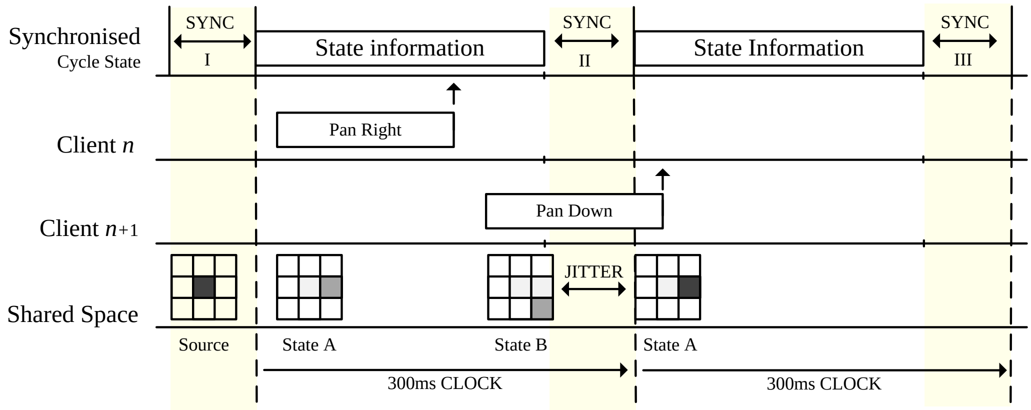

Figure 4.19: Distributed Coordination Mechanism.

SYNC-I
PM: Previous SYNC cycle has already occurred, state updates were distributed.

CN: Client is in its initial 'Source' state, as seen in the fourth row of Figure 4.19.

SYNC-II
CN: Client submits a status update 'pan right' at approx 20ms into the sync-ii cycle. Client's local state = 'State A', as seen in the fourth row of Figure 4.19.

PM: Due to network delays the state update is received late approx 150ms into the sync-ii cycle, validated by the state manager and queued for distribution in sync-ii. Global state = 'State A'.

CN: Client submits an additional state update 'pan down' at approx 180ms into the sync-ii cycle. Clients local state = '*State B*', as seen in the fourth row of Figure 4.19.

PM: Due to network delays this packet is not received during the current sync cycle. Global state = '*State A'*.

In this situation the local client state differs from that of the global state, causing the local state '*State B*' to be forcefully updated to an outdated global state '*State A'* during sync-ii.

SYNC-III

PM: The state update from the client finally arrives=, approx 30ms into sync-iii cycle, validated by the state manager and queued for distribution in sync-iii. Global state = '*State B*' state.

PM: During sync-iii client is reverted back to its correct local state '*State B'* causing a jitter effect to occur.

Given the nature of mobile cellular connectivity, network delays naturally occur, resulting in an observed jitter effect. To overcome this issue, the state synchronisation approach is augmented with a time stamp UTC (Universal Coordinate Time) that gets attached to each state packet.

The UTC time stamp can then be used by client side logic Kalman filters [Chui and Chen 1987, Harvey 1990] to compare incoming state data against previously submitted state data, allowing older state packets to be removed and to eliminate jitter effects. Performing this action client side rather than on the server reduces bandwidth as local state data doesn't need to be updated as frequently, introduces self managed nodes and results in the infrastructure being more resilient to network outages.

4.5.1.3 Distributed Exchange Engine

The distributed exchange engine (D|EE) is responsible for enabling the exchange of resources among connected nodes and monitoring the consumption of such resources. The exchange process (i.e. the upload and download) of resources comprise the core of the distributed exchange engine and provides a unified transfer mechanism to all connected nodes. The distributed exchange engine is outlined in Figure 4.20 and discussed further in 4.5.1.3.3.

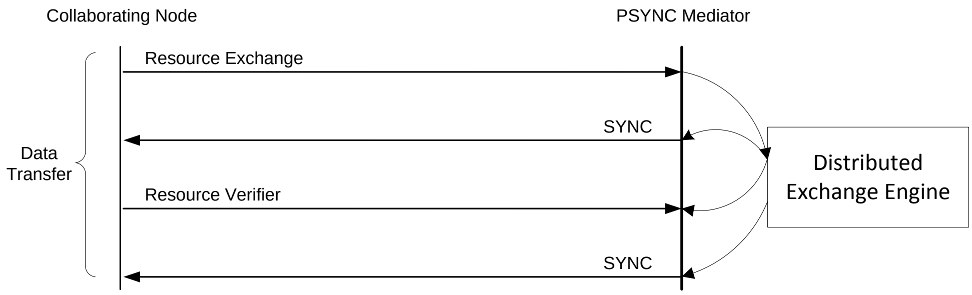

Figure 4.20: Distributed Exchange Engine overview diagram, see protocols 4.5.1.3.3-5 for additional information.

The distributed exchange engine is also responsible for the monitoring of resource consumption across connected nodes. The management of resource consumption assists in the maintenance of resources among nodes during a shared session by providing proof of resource delivery and return to sender information ensuring quality-of-service and fault tolerance in spite of intermittent connections across cellular networks.

4.5.1.3.1 Store and forward process

Mobile data networks can suffer from intermittent connectivity issues, signal loss and times when their users may not wish to be disturbed. As such there needs to be a set of procedures to handle communication between participants if one is actively unavailable or out of signal range.

The Mobile Exchange Architecture therefore offers a store-and-forward (S&F) function, in which if the message cannot be delivered to the receiver straight away, the original message will be stored at the PSYNC Mediator unaltered, which will then be forwarded the intended recipients when they become available.

This is similar to that of a traditional postal service, in which a mail carrier will attempt to re-deliver a registered message if the intended recipient was not at the premises or otherwise engaged during the first attempted delivery.

This comprises basic functionality, but future expansions to the PSYNC Mediator S&F functionality could be enhanced to include the use of live presence information to better inform the scheduling of forwarded messages.

4.5.1.3.2 Security and Encryption

The MEA supports Certificate Authority (CA) root certificates issued by various companies. A CA root certificate provides a trusted third party to verify the ownership of SSL certificates issued to companies and websites. When communicating over SSL, the root certificate on the PSYNC Mediator must match a trusted root certificate on the mobile node in order for the synchronisation to take place.

For secure shared sessions it is not recommended to enable data exchange without having a matching set of root certificates on the PSYNC Mediator and mobile node. If the root certificate on the PSYNC Mediator does not exist in the list of trusted root certificates on the mobile node, the communication will not commence unless the certificate is installed or updated by the user.

4.5.1.3.3 Data Exchange Protocols

Similarly communications between the Connected Node (CN) and the Push-Sync Mediator (PM) are covered in the dialogue based representation below, providing insight into the information exchanged between both parties and their roles in the data exchange process. Only the dialogue between a single connected client and the Push-Sync mediator is highlighted, however the process applies to all connected clients. (CN~) denotes the circumstances where the presence of additional connected session nodes effect the data exchange process being discussed.

4.5.1.3.4 Resource 'transfer' process

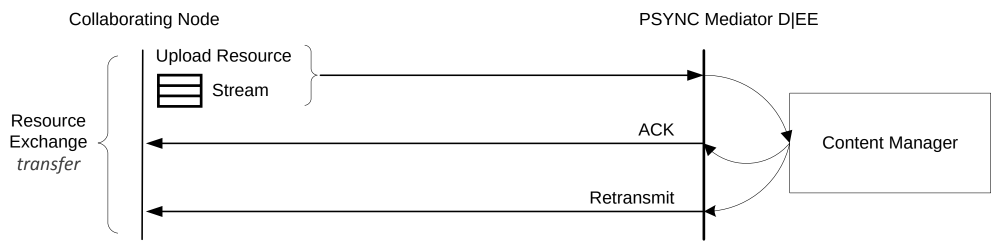

Figure 4.21: Media Exchange Engine.

CN~: Media data is exchanged less frequently than state information during an active session, but amounts to substantially more data being transmitted. Media transmission is lossless with no compression or scaling conducted at the D|EE level e.g. A JPEG image will be transmitted in the original resolution at which the image was captured prior to transmission. This ensures the quality of the media is maintained among connected nodes in the shared session and, if required, application specific compression and scaling can occur at a higher API level prior to hand over, see Figure 4.21.

CN: The resource transfer process consists of a HTTP transfer stream between the connected node and the content manager.

PM: The data stream is received by the content manager, checked to insure correct formatting, header checksums and recipient validity before returning one of two responses to the initiating node:

- ACK: This status acknowledges the transfer of resources and data delivery to the initiating node.

- Retransmit: This status occurs during a transmission error, caused by user interruption, checksum errors or loss of connectivity.

CN: If ‘ack’ (acknowledgement) status is received the transfer process concludes and the node is free to transmit another resource to the active session.

4.5.1.3.5 Resource ‘verifier’ process

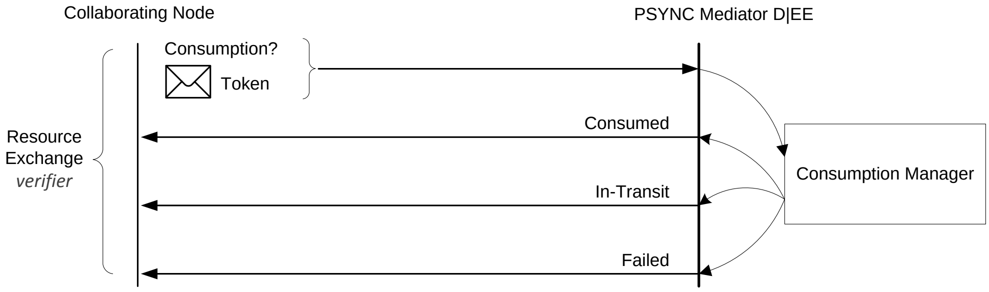

Figure 4.22: Media Exchange Engine.

CN: The connected node submits a consumption verifier token to the consumption manager to confirm the delivery or consumption of a resource, see Figure 4.22.

PM: The token data is received by the consumption manager, checked to insure correct formatting, header checksums and recipient validity before returning one of three responses to the initiating node:

- Consumed: The status denoted that the resource was consumed correctly by the targeted node.

- In-Transit: A retuned ‘in-transit’ status means that the resource has not yet been consumed, but is currently in the process of being transferred to the targeted nodes.

- Failed: The target node, did not receive the transferred resource.

4.5.1.4 Adaptive Throttling Mechanism

In a shared session users can typically perform several interactions at once during the simultaneous transmission or retrieval of media content, which can overextend the device's capabilities. To overcome this, in addition to optimising the on-screen effects and re-sampling of onscreen components, data throttling mechanisms are needed throughout all networking activities, to provide prioritisation to immediate user interactions and enable content retrieval with minimum disruption to interface elements.

On the server side this is used to manage access to resources, provide a level of server reliability, and fall over. Adaptive throttling provides queuing and prioritisation of messages as needed, minimising the need for each mobile node to perform these services. An application specific implementation of the client side (Mobile Node) is covered in more detail in the next chapter.

4.5.2 Collaboration APIs

The APIs comprise the middle layer of the mobile exchange architecture (see Figure 4.23). The application programming interface (API) provides a set of implemented libraries and a structured programming model that minimises the need for deployed applications to directly access the inner workings of the PSYNC layer, reducing the complexity of building mobile media exchange applications.

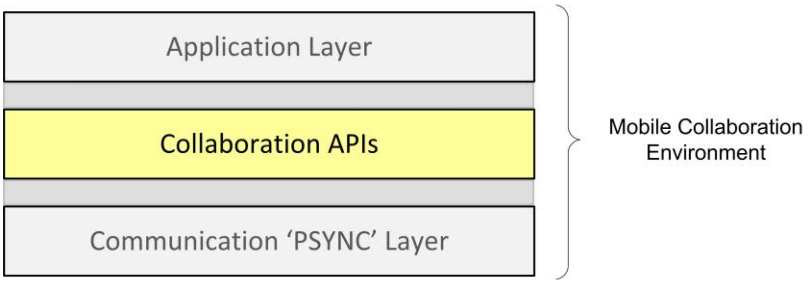

Figure 4.23. Mobile collaboration API layer.

From a development standpoint the APIs provide a set of elevated peer-to-peer primitives that provide unified access to the rich communication functionality of the MEA. This in term allows developers writing to the MEA to focus more on the scenarios they wish to deploy and less on the technical aspects of such services, such as how to send data or establish peer-to-peer sessions. The APIs are made up of publish-subscribe [Eugster, Felber et al. 2003] and session event modules, with each action forming one of three events (see Figure 4.24).

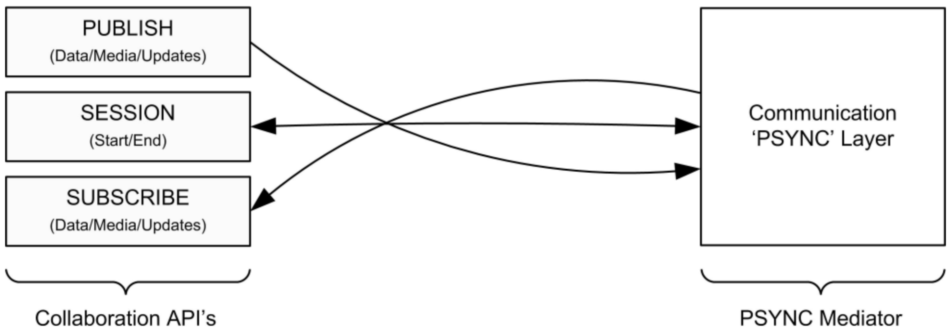

Figure 4.24. MEA application programming interface.

4.5.2.1 Session Management

The session management module enables the creation of peer-to-peer sessions between two or more mobile devices. This is also the first step that an application needs to take in order to engage in communication with another mobile device (mobile node). In order to create a session, the application requests a session creation method and passes a single argument specifying the target destination (the mobile node they wish to connect to), the module then handles the process of establishing a session (see PSYNC session creation process) and returns either an okay or fail status to the user.

The session manager can establish an unlimited number of sessions to other devices at the same time. This allows the creation of a single session then the invitation of other users to join the active session. Session termination is also accommodated by a call to this module passing the parameter of target device, which can be circular (the current device) or a target device that was invited into the session by the user.

4.5.2.2 Resource Publisher

The resource publisher performs the role of the outgoing mailbox in mobile nodes and enables the efficient transmission of data to other devices in the session. The resource publisher supports an arbitrary number of data types through a pluggable architecture and is optimised for the transmission of prioritised control packets (usually textual in nature: for informing other clients of status updates and the activities of other clients) and the much larger binary packets (that comprises the rich data files, music, pictures or movies that clients may wish to exchange with one another).

There is currently no restriction on the file types or sizes that can be transferred to other participants during a shared session using the publishing module. The file transfer capabilities have been tested with 700Mb multimedia files transfers over WiFi and 200Mb over 3G cellular connections. The transfer function supports error correction, with the maximum transfer limits being arbitrary based on the bandwidth available on the given network.

4.5.2.3 Resource Subscriber

In addition to sending files, applications can also subscribe to files sent to them by other mobile nodes. Rather than setting up a subscription to a specific node, this module adopts a self subscription model in which mobile nodes subscribe to files for which they are the target. This simplifies the process and allows client side filtering of received files.

4.6 Chapter Summary

Communication in a static network differs significantly from that of synchronous communication in a mobile network. In static networks, one implicitly assumes that all user devices have stable connectivity while this isn’t the case in a mobile environment. Because mobile networks suffer from weak and intermittent connectivity, a user might become temporarily unavailable even though he or she is still engaged in the shared session.

In this chapter we have presented a new mobile-to-mobile architecture that we believe overcomes the problems inherent in today’s mobile networks. Our architecture offers rich interactional mobile-to-mobile capabilities that can operate throughout existing 3G networks and demonstrates the capabilities available within existing mobile networks to communicate, control and exchange data between remote mobile devices.

The architecture consists of a suite of bespoke client and server based components and protocols to enable rich cooperative services amongst mobile clients. This combination has a number of advantages in the mobile environment. It (1) enhances performance by vastly reducing unnecessary data exchange, (2) maximises bandwidth through built in compression and throttling mechanisms, and (3) enables support for disconnected operations and loss of connectivity.

The mobile exchange server's mid-range hardware (2 x 1.8 GHZ Intel Core 2 Duo, 512 MB RAM, 80 GB SATA Hard Disk, Apache/2.2.11 (Unix), mod_ssl/2.2.11, OpenSSL/0.9.8i, DAV/2, mod_auth_passthrough/2.1, mod_bwlimited/1.4: running on a shared hosting server in Colorado, USA) was tested with a load of fifty concurrent connections, originating from the UK. The server load presented as user load time (see Figure 4.25, left) and bandwidth usage (see Figure 4.25, right). For the peer-to-peer load testing a total of 2,969 random session requests was performed over a 30 minute period. The server load delay in seconds was 4.45 for 10 concurrent clients, 3.98 for 20 clients, 3.78 for 30 clients, 3.83 for 40 clients and 3.69 for 50 concurrent clients. The bandwidth usage in kbits was 482 for 10 concurrent clients, 901 for 20 clients, 1338 for 30 clients, 1849 for 40 clients and 2312 for 50 concurrent clients. The overall server load (i.e. cpu/memory/bandwidth) for this period was under 10% providing resources for additional concurrent connections. Furthermore the use of open web standards and Apache (for data exchange) allows the photo-conferencing service to scale using existing industry standard load balancing and server replication techniques.

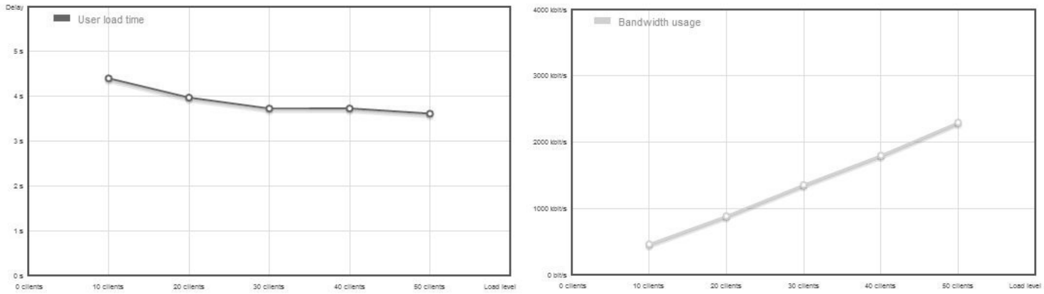

Figure 4.25. User load time (left) and Bandwidth usage (right), for fifty concurrent user sessions.

The creation of a robust distributed co-ordination engine facilitates the management of all active cooperative sessions and supports scenarios from simple media- and location-sharing services to distributed gaming utilising an extensible systems architecture.   The system demonstrates rich interactional P2P capabilities that can operate throughout existing 3G mobile networks.

Some of the possible usage scenarios of this architecture extend to multimedia data sharing, DIY assistance, e.g. "which button should I press – look, they all seem to be red" and to professional field engineers, e.g. "just sent you the latest schematics, let's look at them and let me talk you through the new alterations before you start repairs" and cooperative map sharing to assist with selecting meeting points. In the next chapter we demonstrate one such application that's built directly on top of the mobile exchange architecture.

Chapter 5.

Mobile Photo-Conferencing Service

"The technologies which have had the most profound effects on human life are usually simple" Freeman Dyson

5.1 Introduction

Research has demonstrated that the "one channel at a time" interaction paradigm of MMS causes many mobile users to be "frustrated when trying to share images remotely and interactively" and that participants need richer capabilities to connect in the moment, undergoing the effort of using multiple devices to achieve ongoing conversations while sharing images [Kindberg, et al. 2005]. Frohlich et al. [2002] suggested "Photo-Conferencing" as a service that could overcome these restrictions and provide a means by which users could engage in interactive computer-mediated photo-sharing practices, supported by a simultaneous telephone conversation, minimising collaborative effort [Clark and Brennan 1991].

In this chapter we present a Photo-conferencing service [Yousef and O'Neill 2007] we have named 'Ripple' that builds upon the exchange architecture reported in Chapter 5 to deliver the first rich media sharing service to realise the photo-conferencing vision across mobile devices. Although other instantiations were also possible with the technology we chose to pursue Ripple as it covered many of the fundamental concepts of mobile to mobile interactions. Here we provide an overview of the user interface design of our photo-conferencing application (Ripple) and describe its many features and functionality that enable rich interactive photo-conferencing.

5.2 Implementation - Application Layer

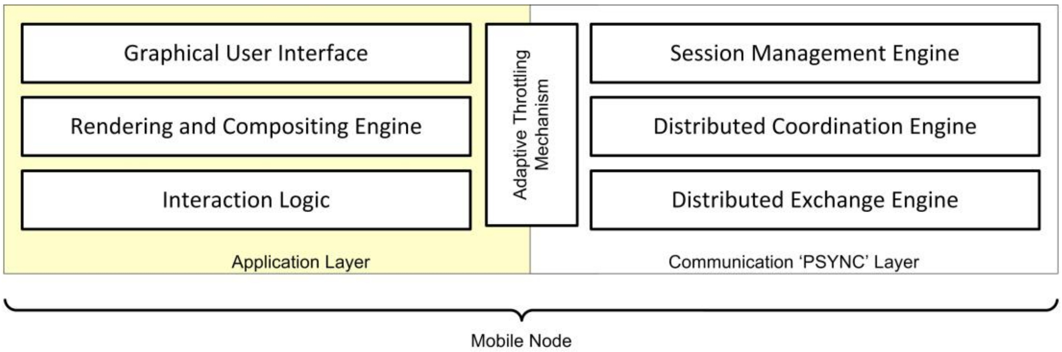

Figure 5.1: MEA application layer components.

Through our work reported in Chapter 5, we developed a complete mobile media exchange system comprising remote mobile to mobile session initiation protocols, client/server based software and application programming interfaces (see previous chapter). In this chapter we report one instantiation of the mobile exchange architecture in the form of a Photo-Conferencing service that resides in the application layer of the MEA (see Figure 5.1).

The requirements for photo-conferencing necessitate the creation of application modules that are beneficial to the process of sharing and manipulating photos among distributed mobile nodes. Taking into account the resource restrictions of mobile devices requires that the core image manipulation modules are highly optimised and any inefficient, replicated or bloated functionality reduced to the bare minimum. To this end the Photo-Conferencing application layer consists of four core elements:

- Graphical User Interface (GUI): Comprises the high level visual elements that the users of the system will see and interact through when using the mobile photo-conferencing service.

- Rendering and Compositing Engine: Comprises the low level optimised encoding, animation, thumbnail creation, image caching, compositing and alpha blending functionality that support higher level GUI elements.

- Interaction Logic: Comprises the primitive subroutines, branching and decision making rules for handling incoming/outgoing data and interactions during the photo-conferencing session.

- Adaptive Throttling Mechanisms: Comprises techniques for enhancing bandwidth, processor utilisation and the maintenance of an acceptable quality of service (QOS) among connected nodes during shared sessions.

5.2.1 Graphical User Interface

Good user interface design can transform an unruly cluster of confusing features into a structured, understandable experience [Donald 2008]. Uday presented 'Experiential Aesthetics' a Framework for Beautiful Experience (see Figure 5.2), that places emphases on creating simplicity in interface design, as users shouldn't need to know about complicated back-end and architectures to get their work done [Uday 2008]. Simple, effective and aesthetically pleasing interface design is particularly important on mobile phones, where users are obliged to interact through very limited physical interfaces.

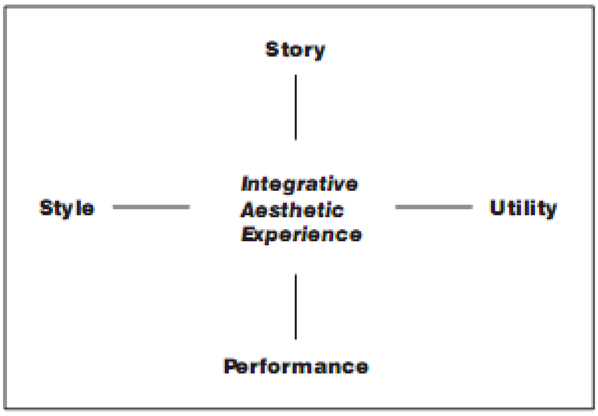

Figure 5.2: Experiential Aesthetics: A Framework for Beautiful Experience [Uday 2008].

As such experiential aesthetics were core to the development of the photo-conferencing service. Each interaction task and subsequent interface screen was created from the ground up with attention to detail extending to even the smallest pixel level. Every screen, selection indicator, load sequence, activity indicator, icons, colour scheme, page titles, input methods etc were carefully scrutinised and iterated many times during the development process to ensure a simple, unique and coherent aesthetic experience throughout.

Research suggests that many everyday tasks aren't planned but are opportunistic, with people simply deciding to use something when they think about it [Norman and Collyer 2002]. The user interface was therefore built to support both Sovereign and Transient states [Cooper and Reimann 2004]. Sovereign states are typically designed to monopolise users' attention for long periods of time. They are optimised for full screen use and to direct the user's attention to the task at hand, e.g. word processors, spreadsheets and e-mail applications. Transient applications, on the other hand, come and go as needed. They are typically invoked only when required and then disappear, allowing users to continue with their normal activities. In designing Ripple we provided support for both sovereign states to maximise screen use during media exchange sessions and transient states in which the application can become active or inactive when the user needs to perform other tasks on the mobile device.

5.2.1.1 Main Task Screen

Figure 5.3: Main interface task selection.

Figure 5.4: Main task selection menu: Start session (top left), Archive viewer (top right), Account settings (bottom left), Exit client (bottom right).

Ripple was designed to enable mobile photo-conferencing between collocated and remote participants. The main application screen provides a clean user interface to simplify this process using task based interactions [Seedhouse 1999, Skehan 2003]. The main application screen (as with the rest of the mobile client) utilises a bespoke user interface designed specifically to support mobile photo-conferencing. The main interface supports four main tasks (see Figure 5.3, 5.4):

- Start session: This item is used to create a new ‘empty’ session. When it is selected users are presented with a list of contacts from the phone’s built in address book. Once a target contact is selected the new session is initiated between the two devices, see section 5.2.1.3.

- Archive viewer: The archive viewer is a chronological data store of all previous sessions created or joined by the current user. All sessions are automatically stored in the archive viewer and presented in chronological order, see 5.2.1.2.

- Account Settings: The settings screen allows the modification of key networking and account management configurations for the user, see section 5.2.1.5.

- Exit Client: Simple option that terminates the application and removes all traces from the mobile's memory prior to exiting Ripple. This option is also available throughout all sub-screens, through the context menu for quick access.

5.2.1.2 Archive Viewer

Figure 5.5: Archive viewer interface (left) and real time rendering process (right).

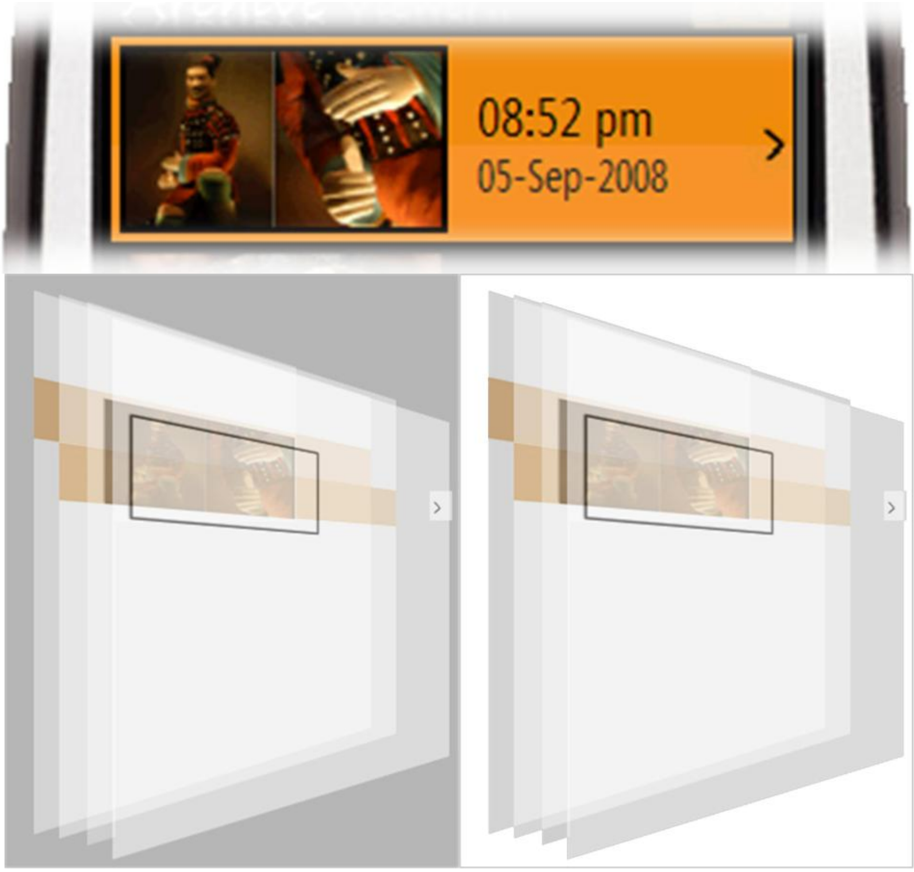

Figure 5.6: Archive viewer real-time overlay process.

The archive viewer can be selected from the main navigation screen and is designed to provide access to previously stored sessions, facilitate the re-spawning of past sessions (e.g. so that they can be re-used in a future session) and to provide users with a visual log of past mobile photo-conferencing sessions from one simple view.

The archive viewer is comprised of a list based representation of sessions, in reverse chronological order with the latest session information and initial picture displayed at the top (see Figure 5.5). The archive viewer utilises a list view representation which provides a flexible set of features and the ability to condense a large amount of data into a representation familiar to most web-browser and operating system users.

Our initial session archives interface utilised the built-in 'ListView' component available as part of the Windows Mobile Compact framework (see Figure 5.5, Left: Standard ListView). However, research suggests that menus constructed of a mixed format (text and icons) result in the fewest number of incorrect selections by users [Kacmar and Carey 1991, Rogers 1987].

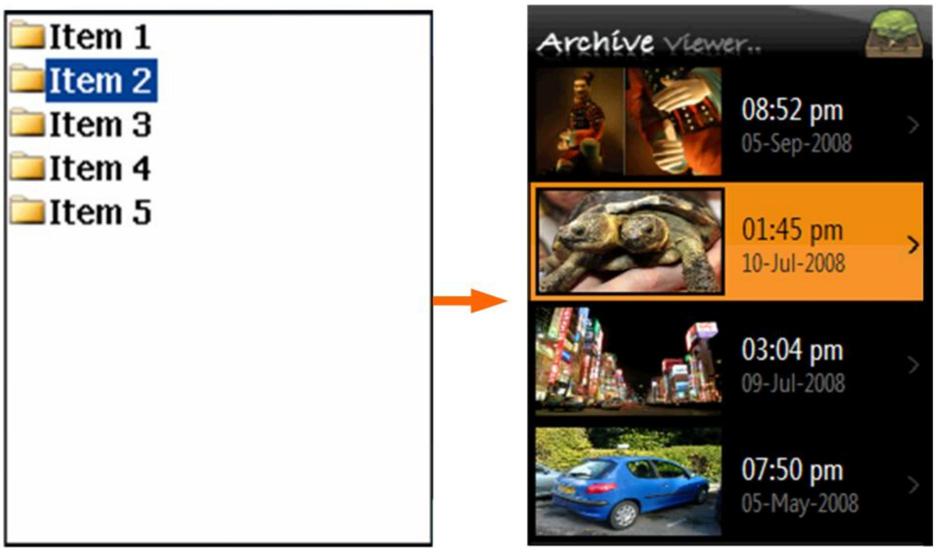

Figure 5.7: Main interface with four options and exit buttons, Standard list view (left), Ripple interface (right).

As part of the iterative interaction design process we sought to improve upon the built in ListView control to provide an enhanced visual representation of past sessions which can more clearly convey past session information and their associated time-stamps (see Figure 5.5 right, 5.6). In addition to the standard controls, recent mobile development tools such as the dot net compact framework provide additional levels of customisation over the creation of user interface control elements. These typically consist of three control levels:

- User controls: Are the simplest type of control. They are most often available through a drag-and-drop visual editor (e.g. Visual Studio), and inherit from the System.Windows.Forms.UserControl class.

- Inherited controls: Are generally more flexible than user controls. With an inherited control, an existing control that closely matches the intended use is selected to derive a custom class that typically overrides or adds properties and methods to the base control.

- Owner-drawn controls: Are the most flexible control class. They generally use GDI+ drawing routines to generate their interfaces from scratch. Because of this, they tend to inherit from a base class like System.Windows.Forms.Control. Owner-drawn controls require the most work and provide the most customizable user interface.

To create the required aesthetic interaction (see Figure 5.7) a bespoke Owner-Drawn ListView control was created specifically for the photo-conferencing application. In contrast to a typical drag-and-drop (e.g. from Visual Studio) 'ListView' control, owner-drawn controls provide the most customisation over the visual elements, the process in which they are drawn and precise pixel placement of those elements.

Due to memory limitations that affected device stability (see Rendering and Compositing Engine 6.2.2) a special image pipeline was created to assist with the creation and caching of thumbnail images. Thumbnails are automatically generated (via the Rendering and Compositing Engine pipeline) for each session and cached to substantially speed up loading times, minimise memory usage and prevent flicker. This pipeline was extended into a complete rendering and compositing engine (see Rendering and Compositing Engine 6.2.2) that is used throughout the application to improve performance and minimise memory use when handling multimedia content.

This technique overrides the 'OnPaint(PaintEventArgs)' method and substitutes our own custom user interface rendering code instead. Though this requires a lot of work it provides a lot of flexibility in the drawing of on screen elements and the optimisation of their loading sequence. See Figure 5.5 (right) for the five stage rendering process.

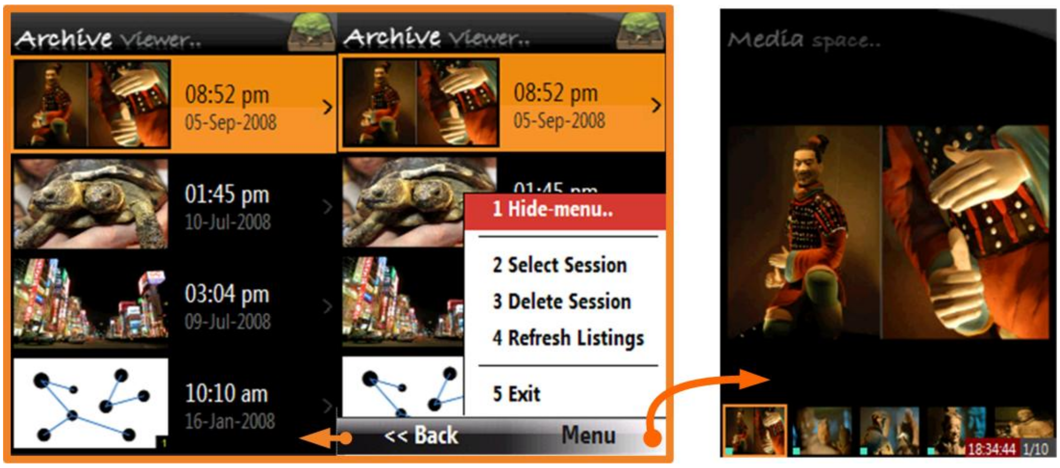

Figure 5.8: Main interface with four options and exit buttons.

Also we need to consider aspects such as: when using a laptop or desktop computer, chances are that you're in a controlled environment; lighting is good, you sit a comfortable distance from the monitor, and using a mouse or track pad to control a screen cursor is a simple task. In contrast, mobile devices may be used in unpredictable situations; outdoors in very bright light, in the course of another activity or while in constant motion which makes coordinated movements difficult to perform. By making the clickable area of an action large, many of these issues are resolved. Additionally when highlighted by a contrasting background colour, important actions are more easily seen and targeted even when overall screen contrast is poor. Most important of all, a large click area requires less precision and effort to activate [MacKenzie 1992].

Ripple utilises a number of these techniques e.g. by varying font size, weight, colour and style, its able to discretely communicate additional information without excessive labelling. Menus are hidden by default (see Figure 4.8) to emphasise the media, therefore most interactions have been designed without menus in mind, e.g. selecting a specific session requires only a right gesture on the arrow key, while returning to the previous screen requires a simple left gesture.

5.2.1.3 Session Initiation Process

Figure 5.9: Session initiation process in action.

The session initiation process occurs after the “Start session” button is selected via the main interface screen (see Figure 5.3), the user is then presented with a list of contacts that are extracted from the mobile phone’s built in address book (see Figure 5.9).

Upon selection of a targeted user for the shared session an “Initiating Connection” screen (see Figure 5.9, right) is presented. This screen animates a waiting state to the user as the underling networking engine determines the existing settings, optimal configuration and whether a new networking connection can be established to the remote target based on the user’s current location, network setup and signal strength.

After the connection has been made, a new session is created and the user is presented with a blank shared interaction “Media Space”, to which new content can be added by either party engaged in the shared session. Additionally from the Media Space screen, at any point in the session users are able to conference-in additional participants, extending the number of users that are currently taking part in the shared session.

5.2.1.4 Media-Space Screen

The Media-Space is the main interaction space for sharing and interacting with images among all users in the shared session. Thus, the media space is comprised of many modular components that can be drawn and manipulated on the screen as needed. This enables users to maintain sessions, share images, interact, e.g. Pan/Zoom, and propagate state changes from a single flexible interface (see Figure 5.10).

At the bottom of the media space lies the image contribution and selection indicator bar (see Figure 5.11, 5.12). This bar provides quick access to all the images shared in the open session so that users can move between multiple shared images (see Figure 5.11). The image contribution indicator presents a unique colour to each participant (computed by multiplying each-user id against RGB colour values), allowing users to determine which image or groups of images were sent from a specific person (see Figure 5.12).

Again due to the large number of on screen images (visible in the centre of the screen and below in the contribution bar), caching and thumbnail generation techniques were used to minimise the application’s memory and processing footprints (using the central Rendering and Compositing Engine). Similar to the rest of the user interface minimalist design, advanced options, controls and user customisable configuration settings (see Figure 5.13) are hidden from the user to maximise screen utilisation but can be called upon with a single click on the phones soft keys for quick access.

Figure 5.10: Main Conferencing Interface.

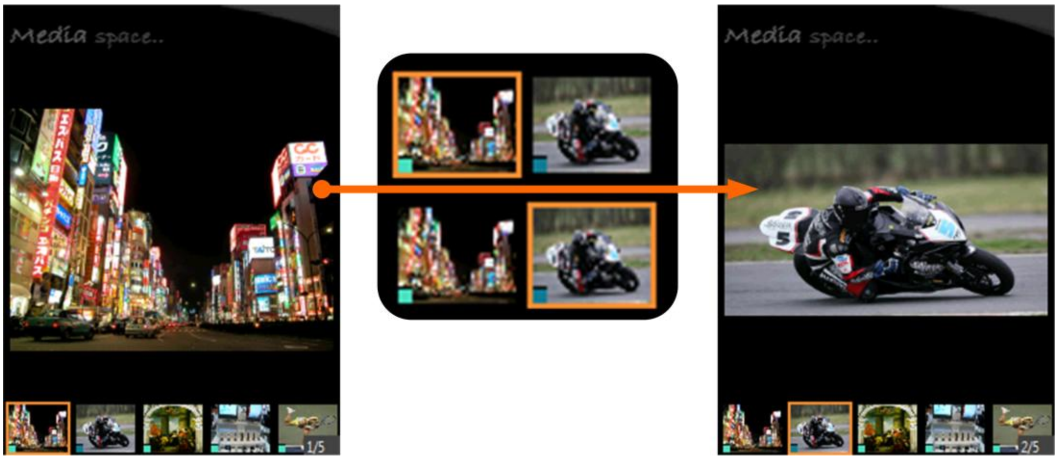

Figure 5.11: Image Contribution and Selection indicator bar: Image selection process.

Figure 5.12: Image Contribution and Selection indicator bar: Image Contribution indicator.

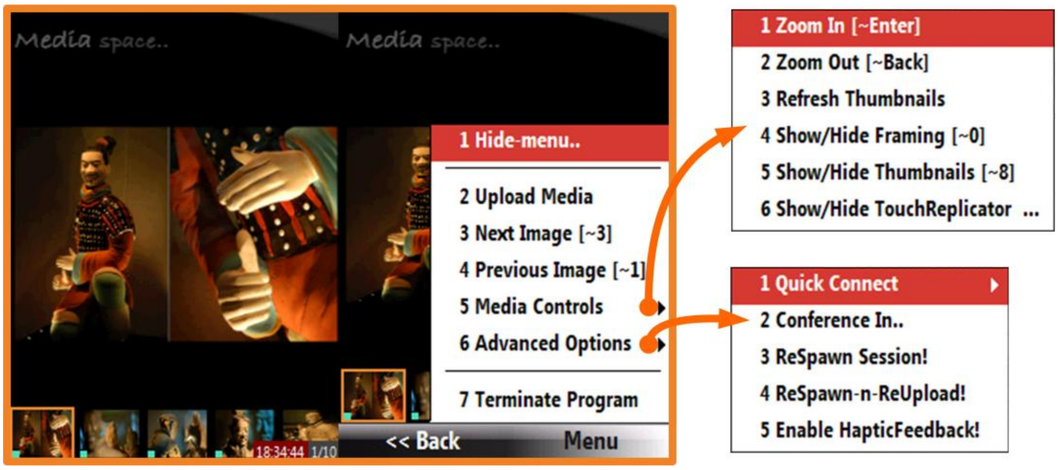

Figure 5.13: Media space advanced options, controls and user customisable configuration settings.

5.2.1.5 Application Settings

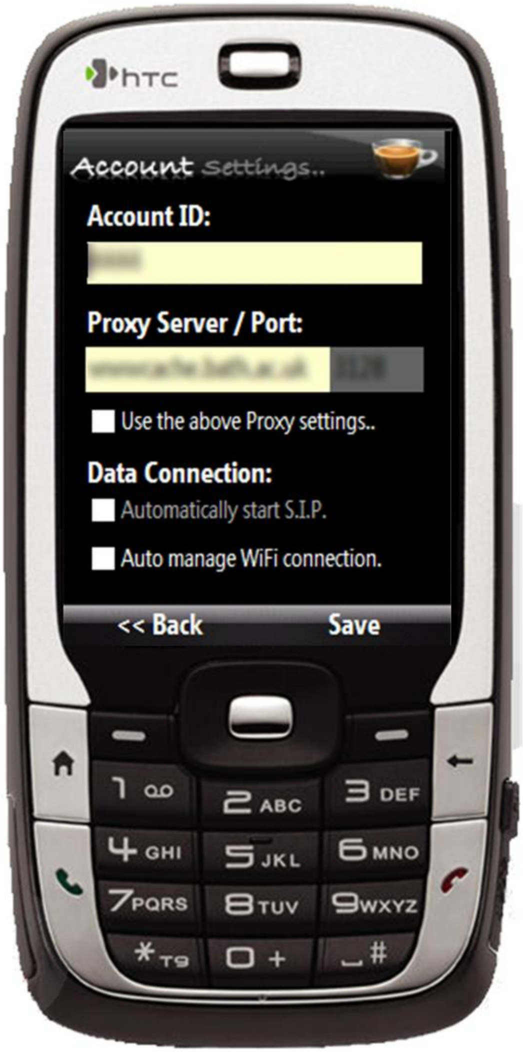

Figure 5.14: Application Settings Screen.

The last Ripple screen comprises of the settings screen which allows the modification of key networking and account management configurations by the user (see Figure 5.14). The account id can be any unique number or character string unique to a user in the MEA network (e.g. this is typically set to the phone number of the mobile device) for easy address book access to mobile nodes. Proxy settings are optional and are only needed when corporate access (e.g. WiFi) restrictions are in place at the organization or network the user wishes to connect to. This built in support for direct proxy configuration ensures network agnostic connections can be maintained even in strict corporate environments.

Finally the data connection options provide additional management of the SIP (Session Initiation Process). When auto-start is enabled, the user is always available to partake in a shared session (though users can ignore an incoming request). This can be disabled when users don't wish to have this functionality, for example when roaming or travelling abroad. The auto-manage WiFi option puts preference on free WiFi based connectivity (when available) over 3G connections to reduce costs or improve data connectivity.

5.2.1.6 User Input Controls

Smartphones were selected over the more powerful PDAs (portable digital assistants) due to their popular compact form factor and because they account for the vast majority of mobile devices currently sold worldwide. Keypads on a smartphones usually have twelve keys, digits 0-9 plus the star and the hash key. In addition, there are typically a number of keys that are referred to as the soft keys. The soft keys are used to navigate and interact within the user interface of the phone and often include a joystick or a set of directional keys.

The Ripple user interface has been primarily designed for single handed use (see Figure 5.15) and facilitates the selection of on screen elements or moving around images during a shared session. Devices that accommodate single-handed interaction can offer a significant benefit to users by freeing a hand for the host of physical and mental demands common to mobile activities [Karlson *et al.* 2006]. For example in a moving subway while clutching a hand strap, the ergonomics involved in non single handed mobile interactions can be very frustrating e.g. trying to control a stylus from moving around a slippery surface.

The input options were designed to take into account three groups of possible users: beginners, intermediates, and advanced. Each has different needs [Cooper and Reimann 2004]. By designing the interface to meet these needs, all these groups will be more satisfied than if it was designed primarily for one group or the other. Also to cater for perpetual intermediates [Cooper and Reimann 2004], the user interface simplifies the interaction to primary use cases, allowing users to perform the main tasks required to establish and interact in a shared session. In addition hidden menus can be quickly revealed to cater for advanced users. This allows users to quickly get the hang of basic functionality then transition to the advanced functionality when needed or after a period of familiarisation.

Figure 5.15: User interface input controls.

5.2.2 Rendering and Compositing Engine

The rendering and compositing engine makes up the backbone of the photo-conferencing service. It's tasked with performing the grunt work needed to ensure the smooth interactions and operations of all on screen components (visible and hidden) during a shared session. Many of the components presented here have been heavily optimised and in many cases are embedded deeply throughout all elements of the photo-conferencing interface.

Given the limited screen space available on the latest mobile devices and the ever increasing availability of high-resolution images (see Figure 5.16) a key prerequisite for any photo-conferencing service is the creation of a group of robust components that can present, manipulate and rapidly animate images on resource restricted mobile devices.

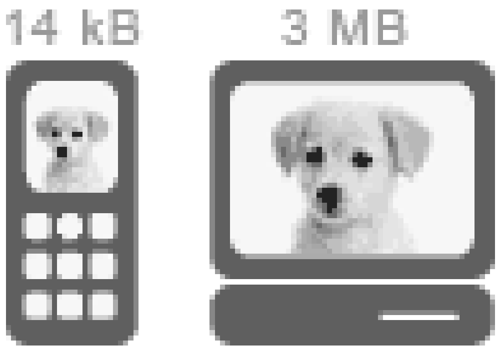

Figure 5.16: Media Exchange relative to screen size.

These requirements were even more important due to the limited processing capabilities of the devices that were available to us (HTC S710: 185Mhz, see Appendix A.1) and also operating system (Windows Mobile 6) restrictions. Windows Mobile 6 (WM6) treats every on screen image as a bitmap; therefore an 800K jpeg image would quickly become 10-50 times bigger in terms of memory required when presented on screen. This issue is further exacerbated by the fact that WM6 operates on top of Windows CE 5 (CE) that severely limits all running applications (including OS total memory use) to 32 MB of virtual RAM.

For example trying to display a 2048x1536 jpeg image (which is about 200Kb in size) which has to be converted by the operating system to a bitmap representation (in memory for display) would result in the 200Kb jpeg image becoming approx 10 MB, resulting in an out of memory exception due to the 32 MB virtual RAM limitation (partly occupied by the OS). We therefore employed a set of bespoke image scaling and robust manipulation functions to support effective photo-conferencing.

5.2.2.1 Scaling & Animation Engine

Figure 5.17: Animated zooming during a shared session.

In desktop systems a typical design problem occurs when interacting with detailed datasets such as map based and network diagram representations in which the available display space is often smaller than the area populated with data. In these scenarios zooming functionality is commonly added to the interface to allow users to navigate around the data space at differing levels of granularity (see Figure 5.17).

Similarly in a mobile photo-conferencing application, the images displayed on the screens usually contain much more additional (pixel) data then can be represented in a single view. Two separate engines were created to assist with these scenarios. The first is a bespoke scaling engine that employs bicubic interpolation and progressive rendering to minimise the memory footprint of on screen items. This allows a zoomed out image (see Figure 5.17 Left) to be optimised to incur a similar small memory footprint to a zoomed in image (see Figure 5.17 Right) by only rendering the required pixels.

In addition a complete animation engine works alongside the scaling engine to assist in performing transitions of on screen components such as performing smooth Panning and Zooming gestural effects. Both engines have been heavily optimised and throttled (using rapid Input and animation tweening to limit the number of successive input events that generate key states over a pre-defined period, see section 5.2.3.2) to minimise the mobile device's CPU utilisation as much as possible and to free up resources for handling the outgoing and incoming networking packets that are essential to maintaining a shared communication session between mobile nodes.

5.2.2.2 Compositing Engine

The conferencing solution consists of a rich user interface that can be initiated at any point during an active voice conversation to enable instant media exchange, and when idle to view prior sessions. The user interface has been designed to support conferencing "What You See Is What I See" (WYSIWIS) functionality, in which media content and gestural interactions are replicated across all connected devices.

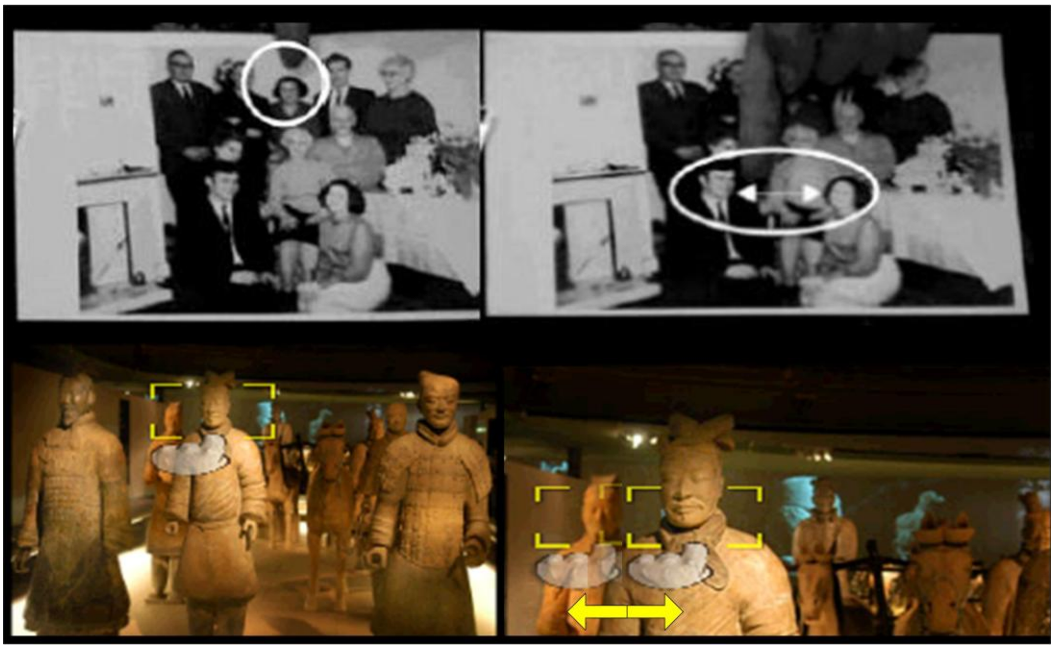

Figure 5.18: Sharing and gesturing as it occurs during face-to-face collaboration [Crabtree, et al. 2004] (top), and during a remote mobile photo-conferencing session (bottom).

The interface currently supports a number of remote media gesturing techniques, Pointing and Zooming (see Figure 5.18), which have been shown to improve performance when working across a large space [Bederson and Hollan 1994, Johnson 1995, Kaptelinin 1995]. These provide the mechanisms through which users can indicate focus during a conferencing session and construct what Crabtree et al. [Crabtree, et al. 2004] describe as "a host of fine grained grammatical distinctions".

Remote gesturing is achieved through an on screen visual pointer (see Figure 5.19) that resembles the working of similar pointing devices found on most desktop computers, with a number of enhancements. The first is the utilisation of a visual pointer hand attached to a selection box to encompass an area of the media providing a sense of reference and focus, and the ability to enlarge and compress the selection area, using similar photo panning and zooming techniques to provide fine grain control over the focus zone.

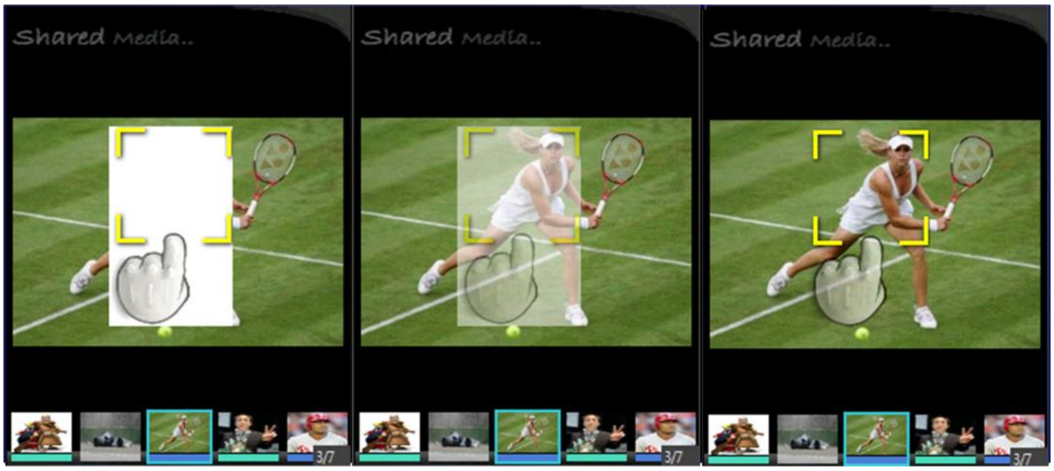

Figure 5.19: RGB (left), RGBA (middle) and RGBA with alpha compositing (right).

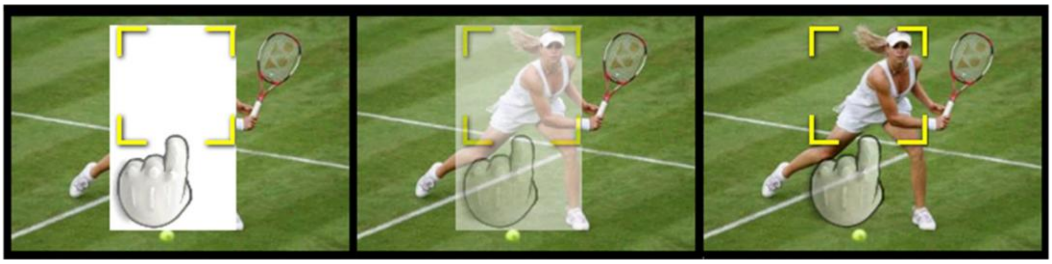

Figure 5.20: Cropped: RGB (left), RGBA (middle) and RGBA with alpha compositing (right).

Because the .net compact framework (the programming layer for the Windows Mobile 6 operating system) on which the system is based lacked support for alpha transparency, we had to create an alpha compositing engine that could take an RGB image and construct an RGBA alpha composited blend that simulates transparency on the pointer.

Alpha compositing is the process of combining an image with a background to create the appearance of partial transparency. Image elements are rendered in separate passes and then combined. The pointer consists of an alpha composited hand (see Figure 5.19, 5.20), that enables direct selection and media focus without obscuring the underlying image. Performance was a major hurdle when creating the alpha composited effect, especially due to the fact that the alpha transparent layer (*the pointer*) doesn't remain stationary but animates under normal usage conditions, as it moves and resizes over the main image.

This work therefore required many development iterations to achieve satisfactory performance results.

5.2.2.3 Content Adaptation Techniques

Enabling mobile to mobile connections, creating shared interaction spaces and careful optimization of the client software has allowed us to extend the photo-conferencing capabilities across a large number of mobile devices currently available on the market, from low-end Smartphones to more powerful Pocket PC devices.

In today's mobile market consumers are presented with a greater choice of devices, form factors and screen resolutions to meet their individual needs (see Figure 5.21). These variations present new challenges to the maintenance of deictic referencing that mobile photo-conferencing services need to overcome in order to succeed.

Figure 5.21: Illustrative example of variations in screen resolution and orientation across a number of available Windows Mobile devices.

Existing mobile photo-sharing solutions such as MMS services have suffered from interoperability issues in which messages created by some devices were not compatible with the capabilities of recipient devices [Bodic 2003, Coulombe and Grassel 2004, Daniel Ralph 2003]. Although MMS interoperability issues still exist today, mobile operators were quick to learn from their mistakes and introduced dynamic content adaptation techniques such as MMSC [Daniel Ralph 2003] to rectify initial user experiences and encourage the adoption of MMS services. Key to the photo-conferencing solution developed in this research is the maintenance of a shared visual space and deictic referencing, through which the mechanics of collaboration [Gutwin and Greenberg 2000] can be supported.

For such a solution to succeed, it needs to overcome such interoperability issues. Support for content adaptation is therefore provided by the photo-conferencing interface. In the following section we present four preliminary techniques: “content transformation”, “content framing”, “content peripheral framing” and “content peripheral t-framing” that enable cross-device content adaptation during photo-conferencing sessions.

5.2.2.3.1 Content Transformation

Content transformation is a technique in which the source (shared) image is modified to accompany variations in the target device’s screen orientation and resolution whilst maintaining deictic referencing (see Figure 5.22). The transformation consists of varying the image’s dimensions and aspect ratio in order to apply stretching across the available display space on each device.

Figure 5.22: The effects of content transformation, as it would appear on a mobile device’s display (yellow area). The top illustration consists of the source image and the lower illustrates the target output.

The top half of Figure 5.22 illustrates the shared visual space as it would appear on the screen of a 240x320 (Portrait QVGA) display, with the bottom half illustrating how it would appear on a 320x240 (Landscape QVGA) display. These are two common screen resolutions, found on many of the latest mobile devices such as the HTC S730 and the Motorola Q9 (see Figure 5.21) respectively. The transformation is applied by manipulating the image's horizontal and vertical aspect ratios according to the target display on which it is being presented.

Suppose Ɽ, Ω are the aspect ratios of the current and targeted displays' resolutions respectively, Cw the current displayed image width and Ch the height. We calculate the target image width Tw and height Th by: $Tw = (Cw \cdot \Omega)$, $Th = (Ch \cdot Ɽ)$.

Figure 5.23: Content transformation, across four devices: S730 (source device), Motorola Q9, HP iPAQ 200 and Apples iPhone. Across four common screen resolutions from left to right 240x320, 320x340, 480x640 and 480x320.

The advantage of content transformation is that it utilizes all of the mobile device's screen real-estate, whilst maintaining an acceptable level of support for deictic referencing, in which a question such as "What colour is the flag in the bottom right?" would return the same answer with both display resolutions (see Figure 5.22, top/bottom). Additionally, when performing transformations to displays which are variant multiplications of the source display, for example displaying the content from a 240x320 (QVGA) device to a 480x640 (VGA) display found on many Pocket PCs such as the iPAQ 200 (see Figure 5.21), no image skewing occurs during transformation, providing identical experiences as both screens share the same aspect ratio (see Figure 5.23).

5.2.2.3.2 Content Framing

Content framing uses subtraction method A ∩ B_{+n} (see Figure 5.24, 5.26 second column), in which both screens permit shared content to be viewed, shading out areas not viewable on both devices. This technique provides an alternative to content transformations and is more suitable for sharing textual and schematic contents across mobile devices as no transformation or skewing is applied to the original image, with horizontal and vertical aspect ratios being maintained.

Figure 5.24: Content framing, across four devices: S730 (source device), Motorola Q9, HP iPAQ 200 and Apples iPhone. Across four common screen resolutions from left to right 240x320, 320x340, 480x640 and 480x320.

Content framing in effect creates blank space at the screens' edges, similar to that observed when viewing widescreen movies on non-widescreen televisions. This allows both participants to interact around an identical shared visual space, without incurring any distortions. In comparison to content transformation, content framing doesn't make the most of the entire pixel repertoire provided by the mobile device. This is even more evident when working between low and higher resolution devices (see Figure 5.24: HP iPAQ 200 and Apple iPhone), in which devices with larger displays are underutilised despite the additional screen real-estate available to them.

5.2.2.3.3 Content Peripheral Framing

Peripheral framing is an enhancement to the content transformation technique used with textual and schematic data, the disadvantage of the earlier approach (content framing) being a reduction in the overall use of available screen space.

Figure 5.25: Content peripheral framing, across four devices: S730 (source device), Motorola Q9, HP iPAQ 200 and Apples iPhone. Across four common screen resolutions from left to right 240x320, 320x340, 480x640 and 480x320.

Peripheral framing adapts techniques from peripheral vision [Rayner 1998] (the part of vision that occurs outside the very centre of gaze). Humans process vision through the receptors on their retina. There are more receptors in the centre of the eye than there are at the periphery therefore vision is better when you are looking directly at an object than when you are using your peripheral vision.

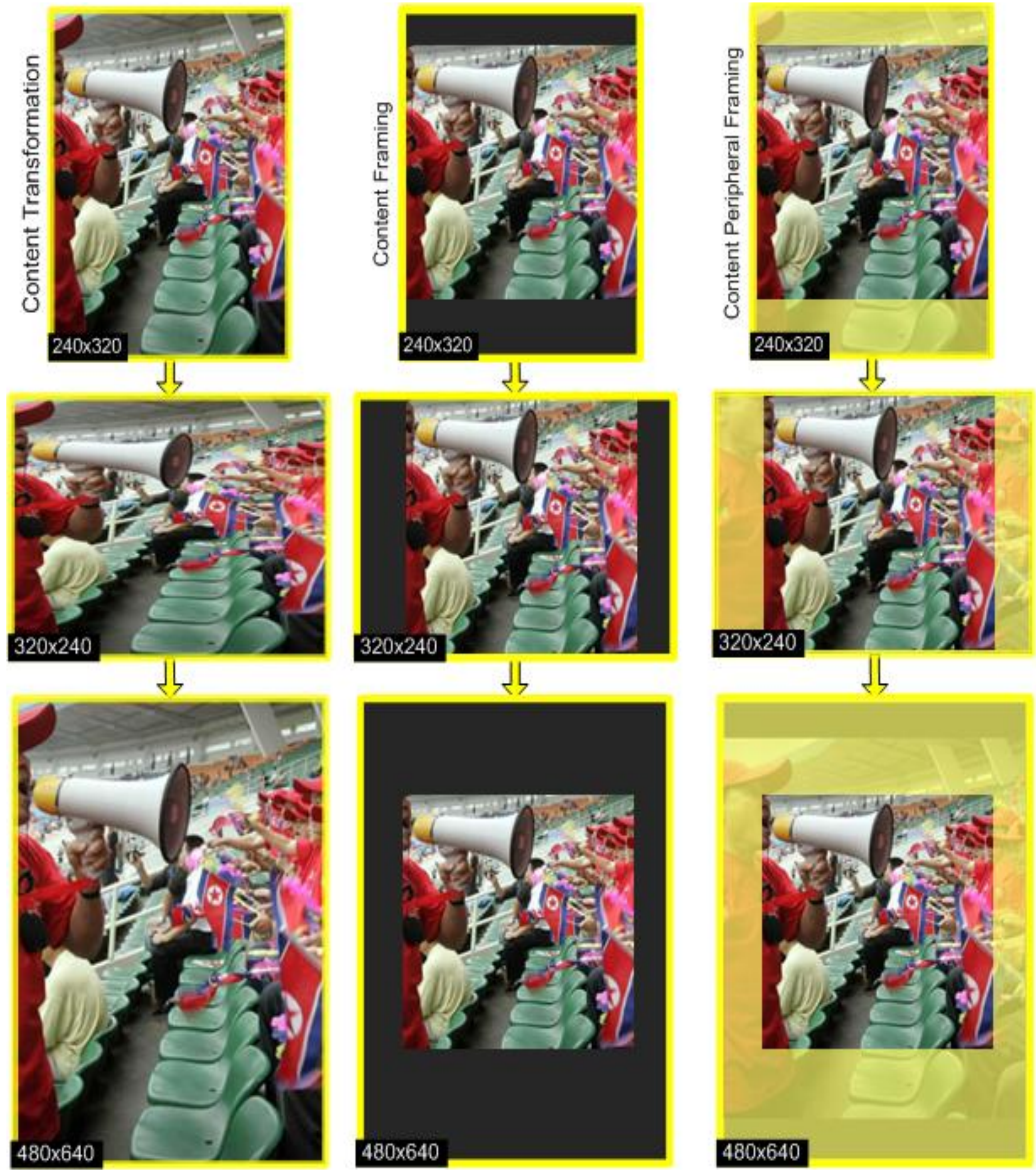

Figure 5.26: An example of content transformation (left) in comparison to content framing (middle) and content peripheral framing (right). Across three screen resolutions from top to bottom: 240x320, 320x340 and 480x640.

In a photo-conferencing scenario, the shared interaction space between all participants constitutes the main point of gaze, whereas the non-shared interaction space can in a similar way to peripheral vision create a paracentral vision adjacent to the centre of gaze, without distracting from the main focus. Content peripheral framing uses the subtraction method A ∩ B principle, shading out areas not viewable on both devices in a similar way to content framing. This allows both participants to interact around shared content, but unlike content framing the applied shading consists of a matt transparency layer that enables peripheral vision to make use of the entire pixel space provided by the mobile device (see Figure 5.25, 5.26 third column).

5.2.2.3.4 Content Peripheral t-Framing

The strength of any photo-conferencing content adaptation method lies in its ability to maintain a shared visual space whilst maintaining acceptable deictic referencing. We have thus far presented three approaches (content transformation, content framing and content peripheral framing) to enable content adaptation during a photo-conferencing session.

Figure 5.27: Content peripheral t-framing, across four devices: S730 (source device), Motorola Q9, HP iPAQ 200 and Apples iPhone. Across four common screen resolutions from left to right 240x320, 320x340, 480x640 and 480x320.

There is however one more approach that should be considered, in which the unique attributes of previous methods can be combined to maximise display usage. Peripheral t-framing is a combination of the best characteristics of content transformation and peripheral framing to further enhance overall screen utilisation.

In this approach content transformation is applied to stretch the shared visual content, filling the available display space without altering the contents' original aspect ratios (see Figure 5.27). Subsequently peripheral framing can be applied to define focus and identify content inside the periphery of the shared space. Using this approach with our previous example (see Figure 5.28, last row), mixed adaptation can be applied to further reduce the need for outsized transparency frames when using peripheral framing, enlarging the shared visual space and further enhancing utilisation of the devices' available screen space.

5.2.2.4 Content Adaptation User Survey

We conducted an environment independent subjective usability survey [Wynekoop *et al.* 1992] in which we asked participants to rate the above content-adaptation techniques to determine the most suitable adaptation methods. The survey presented users with two prototype display screens. The first presented a standard image (see Figure 5.28), the second presented a textual-schematic data (see Figure 5.29), each presented across four common device resolutions by condition: Stretching, Framing, Peripheral Framing, and Peripheral t-Framing (similar to Figure 5.28, 5.29).

We ran 23 participants. Participants were selected at random from students at the University of Bath. The average participant age was 26 and 43% of participants were female. The users were asked to rate the adaptation method they most preferred based on their subjective preferences, see Appendix C.1. To minimise influence participants were not informed as to the nature of the results we wished to collect, e.g. quality of output, readability or distortion between the adaptation methods.

Figure 5.28: An example of image-content transformation (top-row) in comparison to content framing (second-row), peripheral framing (third-row) and peripheral t-framing (bottom-row), across four common screen resolutions 240x320, 320x340, 480x640 and 480x320.

Figure 5.29: Schematic- content transformation (top-row) in comparison to content framing (second-row), peripheral framing (third-row) and peripheral t-framing (bottom-row), across four common screen resolutions 240x320, 320x340, 480x640 and 480x320.

Results for the image based adaptation survey indicated the majority of users (73.91%) preferred Peripheral t-Framing. The remaining (26.08%) preferred transformation and none (0.0%) preferred framing or peripheral framing. A one-way ANOVA across the four conditions found a significant effect on user preference ($f_{3,88} = 27.716$, $p \leq .002$). Post hoc pairwise two-tailed, independent t-tests found a significant difference between transformation and framing ($t_{44} = 2.78$, $p \leq .002$), transformation and peripheral framing ($t_{44} = -2.78$, $p \leq .002$), transformation and peripheral t-framing ($t_{44} = -3.61$, $p \leq .002$), framing and peripheral t-framing ($t_{44} = -7.89$, $p \leq .002$) and between peripheral framing and peripheral t-framing ($t_{44} = -7.89$, $p \leq .002$). No significant difference was found between framing and peripheral framing ($t_{44} = 0$, n.s.).

Users' feedback suggests they preferred the "internal proportion of a shared photo remain the same" and they "don't want someone else to crop/stretch images" for them. The wasted screen space under content Framing was regarded as a restricting factor given the already limited pixel range and screen resolutions available on most mobile devices.

Results for the textual-schematic based adaptation indicated the majority of users (65.21%) also preferred Peripheral t-Framing. Of the remaining users, (21.73%) preferred Peripheral Framing, (13.04%) preferred Stretching and none (0.0%) preferred framing. A one-way ANOVA across the four conditions found a significant effect on user preference ($f_{3,88} = 5.511$, $p \leq .002$). Post hoc pairwise two-tailed, independent t-tests found a significant difference between transformation and peripheral t-framing ($t_{44} = -4.19$, $p \leq .002$), framing and peripheral framing ($t_{44} = -2.47$, $p \leq .05$), framing and peripheral t-framing ($t_{44} = -6.42$, $p \leq .002$) and between peripheral framing and peripheral t-framing ($t_{44} = -3.23$, $p \leq .002$). No significant difference was found between transformation and framing ($t_{44} = 1.81$, n.s.) and transformation and peripheral framing ($t_{44} = -7.66$, n.s.). Users' feedback suggests that this approach "contains a greater level of detail".

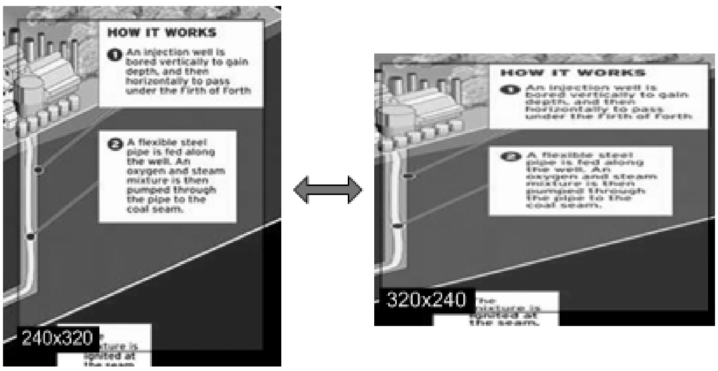

Figure 5.30: Content transformation applied to schematic data containing textual content. 240x320 (right) and transformed aspect ratio 320x340 (left), the textual content in the transformed output becomes harder to read.

From the results Peripheral t-Framing consistently provided a suitable representation of data across device resolutions. In contrast not all images were suitable to undergo content transformations in which skewing occurred. Schematic and textual content can become much harder to read after content transformation has been applied (see Figure 5.30). Individual preferences and perceptions can also be affected by content transformation that results in skewing, in which, for example, the display of loved ones in a stretched aspect ratio can be disconcerting.

5.2.3 Adaptive Throttling Mechanisms

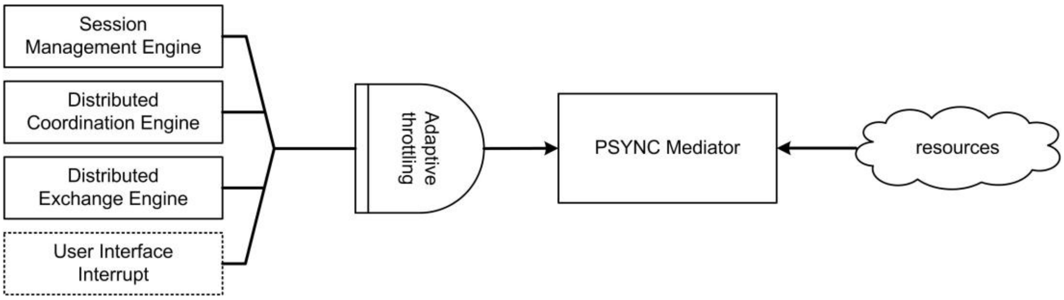

Figure 5.31: Adaptive Throttling Mechanism.

Multimedia streaming over wireless networks is becoming increasingly popular [Harper, et al. 2007]. Adaptive solutions are proposed to compensate for high fluctuations in the available bandwidth to increase communication quality. Throttling is proposed as a client/server technology responsible for ensuring a consistent level of performance, responsiveness and usability during a shared session.

In a shared session users can typically perform several interactions at once during the simultaneous transmission or retrieval of media content (see Figure 5.31). If not managed correctly, these rapid transactions can often overextend the bandwidth available on mobile networks and the processing capabilities of the mobile nodes to analyse such packets.

To overcome this, in addition to optimising user interface components (e.g. display creation, animation effects and re-sampling of onscreen components) to minimize processor and memory loads, data throttling mechanisms are needed throughout all networking activities, to provide prioritisation to immediate user interactions and enable content retrieval with minimum disruption to interface elements.

The adaptive throttling mechanisms outlined in this section perform the automatic queuing and prioritisation of incoming messages as needed, saving each of the connected nodes (which have limited resources) from having to perform these services.

5.2.3.1 Consistency Maintenance Algorithms

Latency is the time required to transmit a message between mobile nodes. Here it is defined as the time between a 'PSYNC' message leaving one mobile node and arriving at its destination mobile node. Network latency is largely unpredictable, particularly across mobile, heterogeneous and wide area networks such as the internet. There are many possible sources of latency in such networks, including the traffic generated by the connected nodes themselves [Dutta-Roy 2000].

As a result of this, latency is rarely constant throughout execution and rich mobile communication is difficult to achieve, regardless of the communication protocols used (e.g. 802.11 protocol family, or wide area wireless communication protocols such as GSM, CDMA, and UMTS). Wireless data connections provide modest bandwidth that fluctuates based on operator coverage and active cell-tower bandwidth. The 'best effort' approach adopted by mobile operators places no guarantees on available bandwidth or packet delivery. These limitations can result in limited connectivity dependent on bandwidth availability and network congestion that can severely affect the exchange of packets between connected participants.

Direct migration from traditional (desktop based) synchronous communication environments is therefore difficult and doesn't result in the same degree of interactivity to connected users. Adaptive throttling is a novel technique to help alleviate these variations in connectivity, speed and signal loss across mobile nodes.

The Consistency Maintenance Algorithms are used to monitor and sense the delay in transmitted packets to dynamically throttle local lag [Mauve et al. 2004]. For example by varying the rate (up: faster or down: slower) at which individual shared interaction spaces are updated, we can minimise inconsistencies across distributed mobile nodes. This can be observed in the following scenario, in which a 'pan right' event is handled differently by a sending and receiving client:

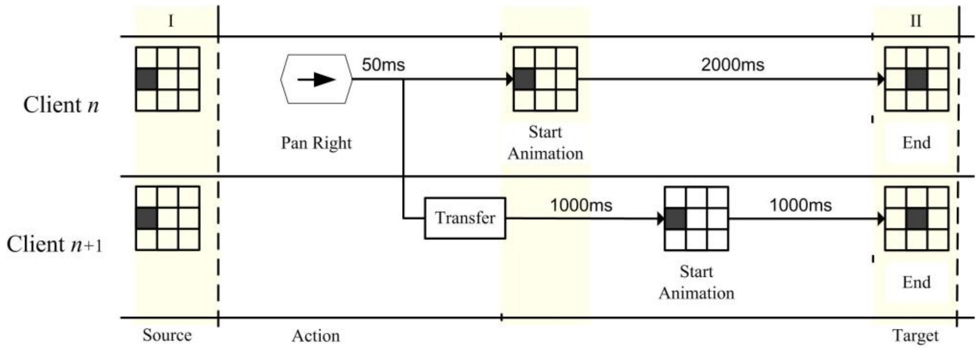

Figure 5.32: Catch-up Coordination Mechanism.

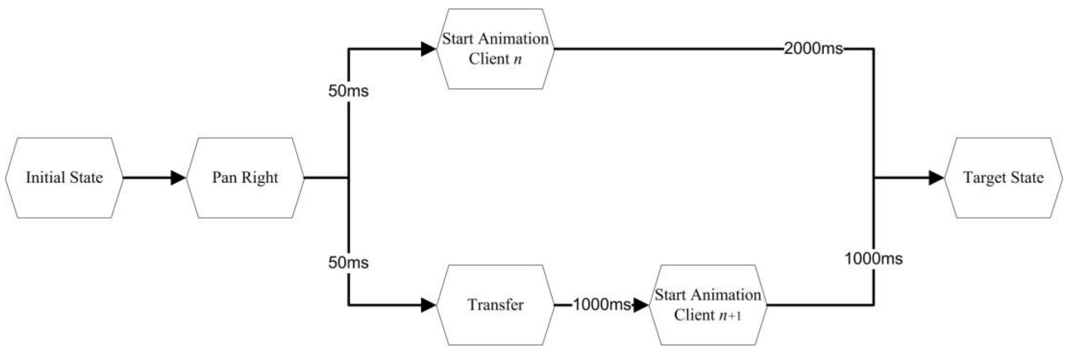

Figure 5.33: Adaptive Throttling Coordination Mechanism.

Here we can see the animation effects used across the shared interaction space for pointing, panning and zooming served two important purposes. The first and most obvious was in providing visual feedback on changes to the shared visual space, similar for example to Google maps [Google] without cluttering the user interface with obtrusive textual event indicators.

The second more novel approach to the utilisation of animation lies in the subtle distractions that can be used to minimise the effects of networking delays between client devices (see Figure 5.32, 5.33). In this approach, when a user pans an image or zooms in on it, the system invokes a 400 millisecond animation transition between the previous state and the target state. During that animation sequence the state data is transmitted for distribution to other clients that animate to the new target state, but at the much faster rate of 200 milliseconds. These variations in animation speeds create a buffer that allows remote connected clients to be perceived as more responsive than they actually are, enhancing the conferencing experience.

5.2.3.2 Rapid Input & Animation Tweening

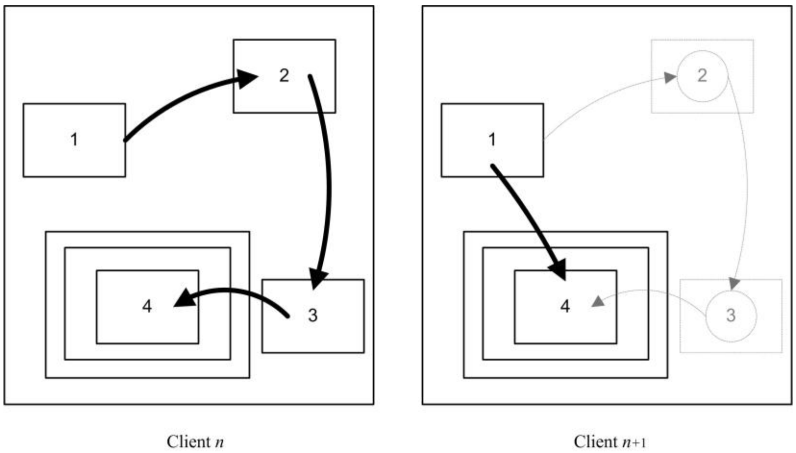

Figure 5.34: Animation Tweening process.

In synchronous communication users can often perform multiple consecutive actions to adjust the shared view or indicate focus to other participants in the shared session. Sending or even receiving rapid inputs puts stress on both the mobile devices and the networks on which they operate.

Rapid input algorithms help reduce network load by only propagating required 'key' state changes throughout the network to other mobile nodes. Key states are defined here as the target state of the interaction in which no subsequent commands proceed within an input threshold. For example if the user changes the state of the shared space by moving around a shared item (e.g. an image) through rapid successive events <300 milliseconds (selected based on informal testing of interaction performance e.g. pan left, pan down, zoom in, pan right on the HTC S710 hardware utilised throughout our testing). The rapid input algorithm will only transfer a portion of the event queue, such as initial interaction and the final destination, see Figure 5.34 right. This cuts down network load and processing requirements on receiving nodes.

However, this introduces jagged flickering state transitions that cause an on screen item (e.g. an image) to bounce around the screen before reaching its final state. This is where the Animation Tweening algorithm comes into play. It complements the rapid input algorithm by smoothing incoming transitions on remote nodes, removing flickering and allowing the seamless movement from the different image states that are received by the mobile nodes (see Figure 5.34).

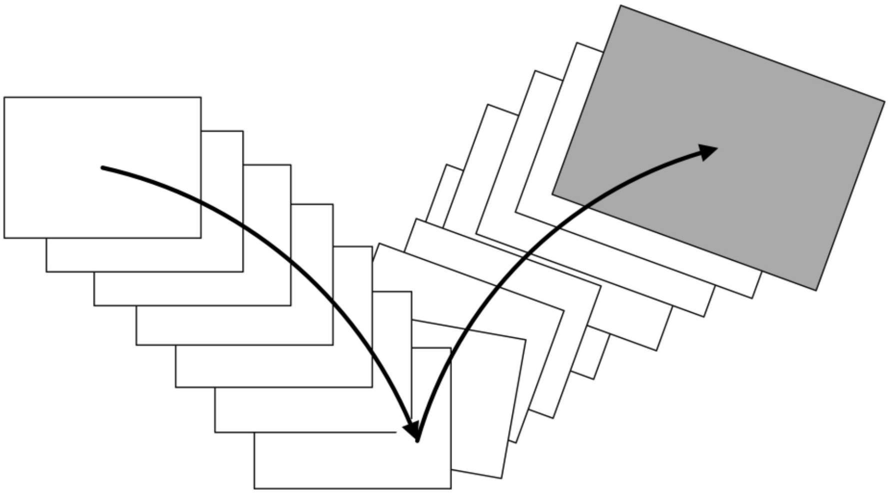

Figure 5.35: Animation Tweening transition.

Tweening is the animation process of moving from an initial state to a target state and is a process supported by the majority of modern animation software packages. Most ways of creating animation involve something called 'tweens'. The word tween is short for in-between. When creating a tween you specify a starting point and an ending point of an animation, and the animation engine does all the work of creating the animation frames in-between (see Figure 5.35).

This allows for the creation of complex animations very quickly by doing the work in the background. There are several different types of tweens: Shape tweens, Motion tweens, Armature teens or Bone tweens. The Animation Tweening algorithm employed by the photo-conferencing service employs a mixture of shape and motion tweens. Tweens work by specifying key-points of an animation (e.g. start state and desired end state) at which point a carefully crafted animation engine (see Scaling & Animation Engine 5.2.2.1) is responsible for computing all frames in between.

Shape tweens are essentially morph animations. By setting the start and end location the engine creates a smooth morph effect automatically (e.g. used by the Zooming interaction). Motion tweens allow the animation of objects along a path that the motion tween follows (e.g. used by the Pointing interaction). Tweening can be combined with the rapid input algorithm to cut down on network load, but can also be used on its own to help mobile nodes better cope with data loss. The tweening algorithm can allow a swift transition between the last transmitted event and the latest received event, without the need to reproduce intermittent (lost) events.

5.2.3.3 Unicast & Group Messaging

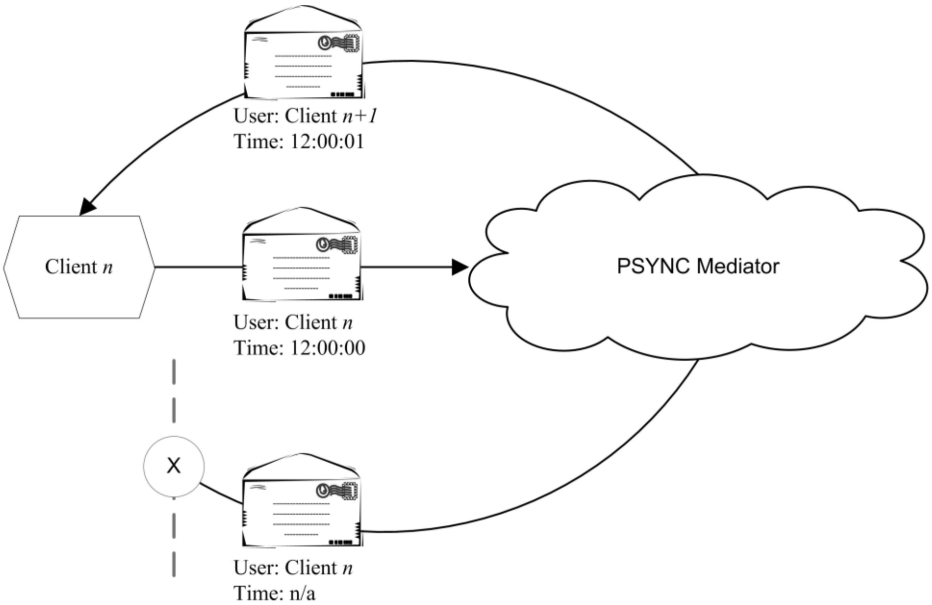

Figure 5.36: Catch-up Coordination Mechanism.

Unicast transmission is employed to ensure that information packets are only sent to the required mobile nodes and not broadcast to all nodes (see Figure 5.36), further reducing network load. An example scenario where this functionality is used is in the elimination of 'echo' in the network. Echo can commonly occur when a status update is broadcast by a mobile node to other nodes in the network. The initiating client as part of the broadcast will also receive the message it transmits to others.

Unicast and select messaging prevents this scenario from occurring by allowing clients to target specific nodes or groups of node in the mobile network (excluding themselves in the process). Target packets bring many advantages such as optimised bandwidth, in which clients only receive the packets destined for them, and reduced processing requirements as no additional filtering is needed client side to ignore echo messages. Additionally the built in support for unicast messaging improves the security and integrity of the MEA network by ensuring the transmitted packets are only delivered to authorised mobile nodes during an active session.

5.2.3.4 Sequencing & Time Synchronisation

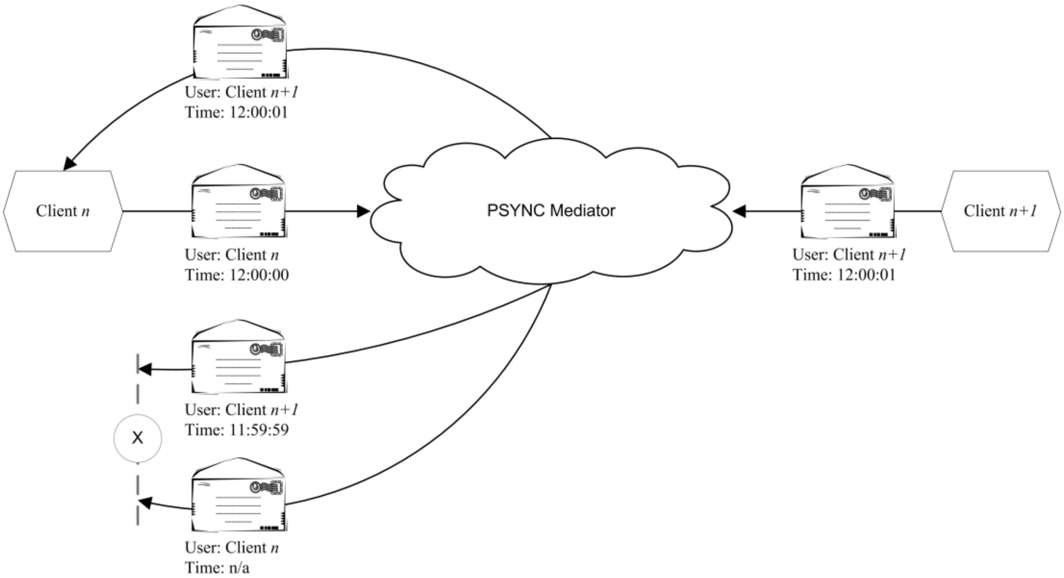

Figure 5.37: Synchronisation Mechanism.

The sequences in which messages are received play an important role in synchronous communication. When using non-fault tolerant networks, packets can be lost in the network or arrive at targeted nodes out of sequence. Both situations are harmful when attempting to maintain a shared view. Lost packets result in jumps in state updates (which the Tweening engine helps alleviate) and delayed packets can result in a *déja vu* scenario in which unintended past events affect a future system state.

By employing a global, millisecond precision (needed for rapid input) shared time across all connected mobile nodes, clients can analyse the time-stamp associated with incoming packets against the time-stamps of previously received and transmitted packets to assess correct ordering. For example if a packet delay occurs, upon receiving the delayed packet the client will be able to identify the time-stamp as being older than a more recent received packet or packet recently submitted by the client, in which case the packet can be discarded in favour of a more up-to-date event thereby avoiding such situations (See Figure 5.37).

To achieve millisecond precision, server side time synchronisation is used over client side time synchronisation. This reduces the need for clients to continuously synchronise their internal clocks or share time zones.

5.3 Chapter Summary

The photo-conferencing service represents our initial instantiation of a mobile media exchange service built on the Mobile Exchange Architecture presented in Chapter 4. Although simple in nature, it tackles three fundamental obstacles of mobile cooperative services: (1) establishing mobile-to-mobile sessions, (2) exchanging large amounts of data, and (3) maintaining a shared visual space among remote cellular devices.

The system supports two working modes, synchronous and asynchronous: one in which real time interactions are shared with all participants and the other in which users can join, leave and catch up later at any time. Scalability was a core part of the architectural design. The photo-conferencing service demonstrates rich interactional P2P capabilities that can operate throughout existing 3G mobile networks and addresses the important issue of mobile content adaptation. Content transformation, content framing, content peripheral framing and content peripheral t-framing techniques are all demonstrated to enable rich media sharing across mobile devices, adapting to variations in screen resolution.

The photo-conferencing interactions enable remote or collocated mobile users to interact with visual media using two shared interaction techniques: ‘pointing’ which consists of a pointer cursor that simultaneously moves on both devices, and ‘scaling’ which simultaneously enlarges or shrinks the viewable area on both devices.

Pointing and scaling on each device can be controlled independently or simultaneously (i.e. synchronously across the devices) using dedicated hardware buttons. These facilities provide a shared visual space that can lead to more efficient communication [Gergle 2005, Kraut, et al. 2002], providing the mechanisms through which users can indicate focus during a collaborative session [Bederson and Hollan 1994, Johnson 1995, Kaptelinin 1995, Turner and Kraut 1992] and construct what Crabtree et al. [2004] describe as “a host of fine grained grammatical distinctions”.

In scenarios when users are distributed, the photo-conferencing system supports simultaneous voice calls amongst the users. This is not, of course, to claim that there will be no differences between collocated (face-to-face) and distributed interactions but, uniquely, our mobile system offers users the ability to use the same mobile device and services with full voice communication across both collocated and distributed settings.

This chapter has provided an initial prototype of a new form of mobile-to-mobile media sharing service that is spontaneous, dynamic and can occur during an active phone conversation. In the next chapter we focus on the interaction techniques used with this service and through a series of user studies assess the impact of these interaction techniques throughout a shared communication session.

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Chapter 6.

Remote Interaction Techniques

“The medium, or process, of our time - electric technology is reshaping and restructuring patterns of social interdependence and every aspect of our personal life. It is forcing us to reconsider and re-evaluate practically every thought, every action” Marshall McLuhan

6.1 Introduction

In this chapter we extend our previous work to evaluate a series of remote mobile interaction techniques afforded by our novel MEA photo-conferencing service. Although the mobile exchange architecture’s instantiation explicitly supports remote photo-conferencing, its interaction techniques have more general application. Our aim here was to understand the effects of the remote gestural techniques on mobile media exchange. In particular, we were interested in their effect on the collaborative effort [Clark and Brennan 1991] required by participants to perform their joint activity.

We report two lab-based user studies of our mobile exchange architecture. The first experimental study evaluates differences between remote ‘Pointing’, ‘Scaling’ and ‘Mixed’ interaction techniques. The second experimental study evaluates a ‘Hybrid’ interaction technique created by combining the most successful characteristics found in our first study. The studies assess the impact of remote mobile interaction techniques on users’ actual performance and perceptions, assessing the individual merits of each requirement to help advance and inform the design of systems to support co-present and remote mobile interactions. Accordingly, the main focus of this chapter is to contribute to the basic understanding of the effects of remote gesturing techniques on mobile interactions.

In addition we report a third, field-based, study which evaluated user engagement with the MEA and suggested implications for the design of such mobile services.

6.2 Grounding Communications

Establishing mutual understanding, or 'common ground', is required for effective communication. This is referred to as the 'process of grounding' [Clark and Schaefer 1989, Clark and Wilkes-Gibbs 1986]. Grounding is a collaborative, interactive process, which ensures that participants have understood a previous utterance, to a level sufficient for their current purposes.

The process of grounding can be affected by several factors. Clark and Schaefer [1989] suggest that different conversational purposes impact on grounding, so task related conversations might require stronger evidence of understanding than social dialogues. It has also been proposed that the process of grounding changes with communicative context [Clark and Brennan 1991]. This is because contexts vary in the number of channels of communication they support, and hence the range of 'grounding constraints' (ways of constraining the many possible interpretations of utterances or messages) afforded by the communicative context. Some methods of grounding appear to require very little effort in communicatively rich contexts, but using the same grounding constraints in another context may take considerably more effort. For example, while it is easy to use non-verbal behaviour to show agreement and understanding in face-to-face communication, this is not so easily achieved during a videoconference, where the visual channel is often impoverished.

The effort required to maintain the process of grounding will therefore vary dramatically with communicative context [Clark and Brennan 1991]. For example, in video-mediated communication (VMC), attenuation of visual signals can make it difficult to time the effective use of non-verbal signals to show understanding.

Similarly users of MEA systems should use the grounding constraints that require the least collaborative effort. The question being addressed in this section is the extent to which the gestural interactions provided by our MEA to support this. Although there have been a number of studies of the impact of VMC on users [e.g. Anderson, et al. 1997, Sellen 1995, Whittaker and O'Conaill 1997], very little research has investigated those effects across resource restricted (form factors, networks and services .etc) mobile cellular devices.

6.3 Pilot Studies - Interaction Techniques

Recent research points to participants needing richer capabilities to connect in the moment and the need for interactivity when sharing photographs: "[domestic photographs] are meant to be shared, and they are meant to prompt interaction" (Chalfen 1998). We therefore developed a complete photo-conferencing system (see Chapter 5), and added support for two interaction techniques 'pointing' and 'scaling' that could be used in combination to achieve such interactivity.

6.3.1 Pointing:

Figure 6.1. 'Pointing interaction.

The photo-conferencing system needed a means to facilitate deictic referencing during a shared session. Area pointing (pointing) was added as it forms a natural interaction and is familiar to using a pointer on a computer screen to indicate areas of focus [English et al. 1967].

This is also demonstrated in studies collaborating around collections of photographs [Crabtree, et al. 2004] in which users are observed pointing. Crabtree identifies ‘pointing’ as “a gloss on a host of embodied interactional gestures that enable persons using photographs to establish mutual orientations, to furnish topics and to make a host of what might, following the later Wittgenstein [Wittgenstein and Anscombe 1953], be called fine-grained ‘grammatical’ distinctions that provide for the meaningful use photographs and the practical achievement of ‘sharing”.

6.3.2 Scaling

Figure 6.2. Scaling interaction.

In addition to pointing based interaction, a scaling interaction was added to aid the display of the details of a given shared photograph due to the inherent limitations of mobile devices’ screens (i.e. minimal size and resolution). Most if not all images captured by the cameras built into current mobile devices offer a minimum of two megapixels resolution images (1600x1200) that greatly exceed the QVGA (320x240) resolutions provided by the majority of mobile device screens.

The act of scaling in and out of an image to indicate detail or focus on a specific subject has been shown to improve performance when working across a large space [Bederson and Hollan 1994, Johnson 1995, Kaptelinin 1995] and can complement the pointing interaction during the collaborative image sharing session, providing the mechanisms through which users can indicate focus during a conferencing session and construct what Crabtree et al. [2004] describe as “a host of fine grained grammatical distinctions”.

6.4 Study 1 – Pointing And Scaling

This first study was motivated by early prototype observations in which we noticed substantial variations in the time required by users to effectively reference on-screen items using the initial interaction techniques offered by the mobile photo-conferencing service. The goal of this study was to examine how the effects of the three interaction techniques that we originally offered (pointing, scaling, and a mixture of both pointing and scaling) affected users' actual and perceived performance with the mobile photo-conferencing service, testing our initial hypothesis:

> *[H1] Providing multiple mobile interaction techniques through our 'mixed' condition would result in better performance, since it offered users a free choice of the two mechanisms to indicate and share focus.*

The study investigated three interface conditions: pointing, scaling and a mixed condition. The 'pointing' interaction consists of a cursor that simultaneously moves on both devices, whereas the 'scaling' interaction simultaneously enlarges or shrinks the viewable content on both devices (see Figure 6.3). The mixed condition offered both facilities and the ability to switch freely between them. The pointing and scaling interactions are designed to be controlled independently or simultaneously on each device (i.e. synchronously across the devices) using dedicated hardware buttons designed for primarily one-handed smartphone usage.

Figure 6.3. 'Pointing' (left) and 'scaling' (right).

6.4.1 Study Methodology

6.4.1.1 Design

The experiment was conducted using a between participants design, which manipulated one independent variable, communication method, consisting of three levels (‘pointing’, ‘scaling’ and ‘mixed’) accompanied by an audio channel to support voice communication.

The dependent variables included: task completion time, number of words spoken, number of input events that took place, error rates and a subjective rating of mental workload by the participants. The experimental hypothesis was that the mixed condition would result in better performance measurements, since it offered users a free choice of two mechanisms to indicate and share focus [Turner and Kraut 1992].

6.4.1.2 Interaction Techniques

Study 1 investigated three interface conditions: pointing, scaling and a mixed condition. The pointing and scaling interactions were designed to be controlled independently or simultaneously on each device (i.e. synchronously by any participant across all devices) using dedicated hardware buttons on the mobile keypad.

- In the ‘pointing’ condition, the participants were provided with only the pointing facility of the mobile media exchange service (see Figure 6.4.c). The ‘pointing’ interaction consists of a cursor with an attached selection area that simultaneously moves on both devices (see Figure 6.3 and 6.4b). In this condition the pointer can be positioned anywhere on the screen using a combination of six buttons: directional-pad (up, down, left, right) for pointer positioning, enter-button to shrink the pointer’s selection area and back-button to enlarge the selection area (up to three levels in either direction). Moving the pointer on one device’s screen made it move synchronously on the other device’s screen.

  The animation speed at which the pointer moves on user input was set to 500 milliseconds to provide smooth transitioning (due to processor limitations) and covers a movement area equivalent to the size of the pointer’s selection box (e.g. 115x65 pixels at level 2 on a 320x240 display).

- In the ‘scaling’ condition, participants were provided with only the scaling facility (see Figure 6.4.ba and 6.4.bb). The ‘scaling’ interaction uses a progressive zooming technique (employing bicubic interpolation) to simultaneously enlarge or shrink the viewable content on both devices (see Figure 6.3 and 6.4a-ab). In this condition images can be positioned anywhere on the screen and scaled using a combination of six buttons: directional-pad (up, down, left, right) for image positioning, enter-button to scale into the viewable area and back-button to scale out of the viewable area. Scaling on one device’s screen made the same scaling occur synchronously on the other device’s screen.

  The scaling interaction is dynamic based on the original image’s resolution (pixel/aspect ratio) which limits zoom to 1:1 of the original image size e.g. a 960x 720 image would support three degrees of zooming from its original zoomed out view (on a 320x240 display).

  Similar to ‘pointing’, the scaling interaction used in the experiment was restricted to three degrees of scaling (each doubling the image size). The animation speed at which the scaling occurs from start to finish on user input was also set to 500 milliseconds due to processor limitations (see Appendix A.1).

- The ‘mixed’ condition offered both the pointing and scaling interaction techniques (see Figure 6.3), and participants were encouraged to use whichever they preferred at any time. The pointing and scaling interactions are designed to be controlled independently or simultaneously on each device (i.e. synchronously by any participant across the devices) using dedicated hardware buttons on the mobile T9 keypad.

  In this condition a toggle-key (hash-button) was added to allow users to switch between the pointing and scaling input mechanisms. An event (pointing or scaling) on one device’s screen made the same event occur synchronously on the other device’s screen.

Figure 6.4. Extract from a complex visual image with multiple points of focus (a): Michelangelo's Last Judgement; (ab) after 1 degree of scaling; (b) with cursor indicator.

6.4.1.3 Experimental Task

Study 1 tested the following hypothesis:

> *[H1] Providing multiple mobile interaction techniques through our 'mixed' condition would result in better performance, since it offered users a free choice of two mechanisms to indicate and share focus.*

We wanted an experimental task which tested users' ability to navigate around shared images on the (small) mobile display and to identify focus points and the connections between them [Crabtree, et al. 2004]. Previous research on referential communication has often utilized experimental situations that create communication challenges for participants in a more condensed way than they typically occur spontaneously [Clark 1996, Clark and Schober 1989, Clark and Wilkes-Gibbs 1990, Kraut *et al.* 2002, Kraut *et al.* 2002].

Therefore, in testing the hypothesis we abstracted away from the details of any particular shared image while controlling the complexity of the task. Following Dillon [Dillon *et al.* 1990] and Kabbash [Kabbash *et al.* 1994], the experimental task utilised a puzzle paradigm which required a Helper to guide the actions of a Worker in the completion of a "connect the dots" diagram.

This was chosen as it represents a generic object-focused task and is comparable to tasks used in previous work [e.g. Clark and Brennan 1991, Zanella and Greenberg 2001], allowing for precise control over the number of referential points used by participants and the level of task difficulty. The dots used in the experimental task represent focus points and the connections represent relations between those focus points (see Figure 6.5).

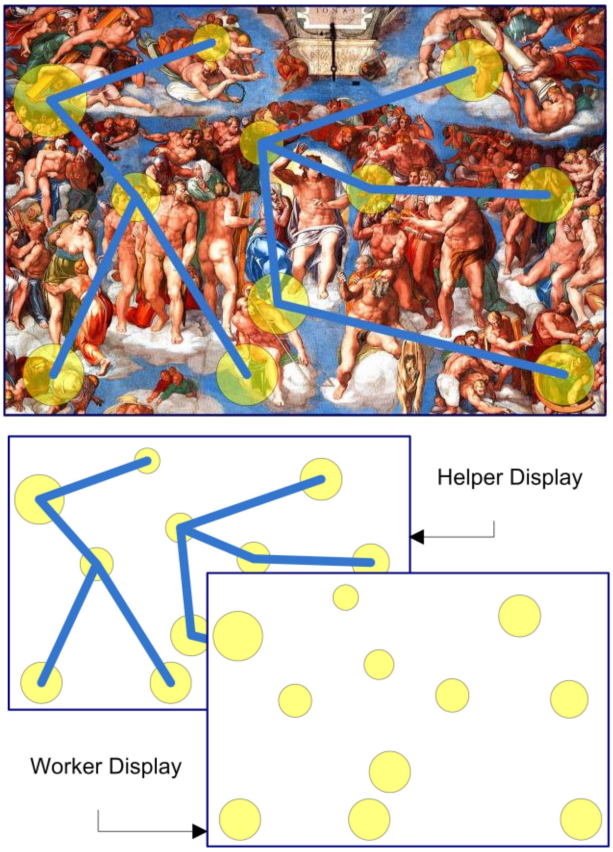

Figure 6.5. Michelangelo's Last Judgement, example image with multiple referential points and connections showing one possible relation diagram.

To complete the task a participant was required to connect a series of dots constructing a unique shape known only to the other participant. Connecting the dots provided a large number of unique permutations (see figure 6.6) to be created, and the Worker relied completely on instruction from the Helper. The task consists of connecting a series of nodes (dots) together; there was only one restriction outlined: "as a minimum each node must at least connect to one other node". However, there was no limit on the number of connections to or from a single node, i.e. a node can connect to multiple other nodes or just one (see figure 6.7).

We measured speed and accuracy of target selection from a standard starting position. In order to extend generalisability beyond simple images, the dots (targets) used in the task differed in position and size and were distributed in an irregular pattern across the screen in order to limit the participant's ability to verbally identify objects directly using physical characteristics alone. This approach was selected to stress users beyond that of simple image sharing and simulate scenarios in which mobile users may interact not only with visually rich images (e.g. Figure 6.5) but also other complex representations such as schematics (e.g. engineering diagrams) or map based representations (e.g. GPS based navigation aids) that may contain many referential points.

Additionally, three different puzzle layouts (see Figure 6.6, Appendix D.4) were utilised across all conditions to counter potential confounding variables or learning bias due to a specific puzzle composition.

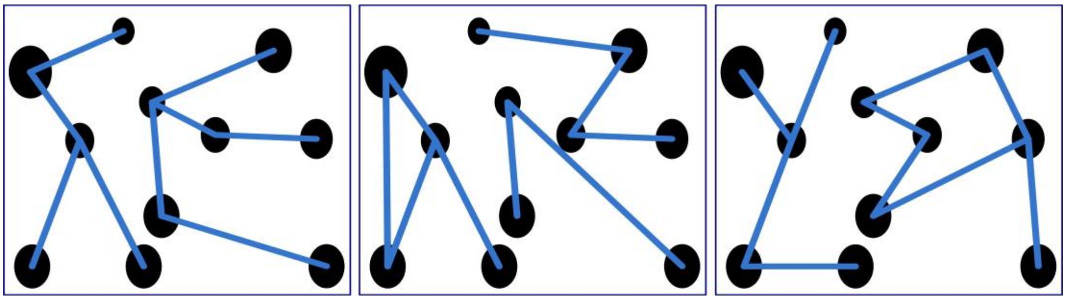

Figure 6.6. Diagram layouts used across conditions and counterbalanced across participating pairs. Rule defines that each node in the diagram mus connect to at least on other node for successful completion. Design allows for a large number of possible permutations to deter random selection.

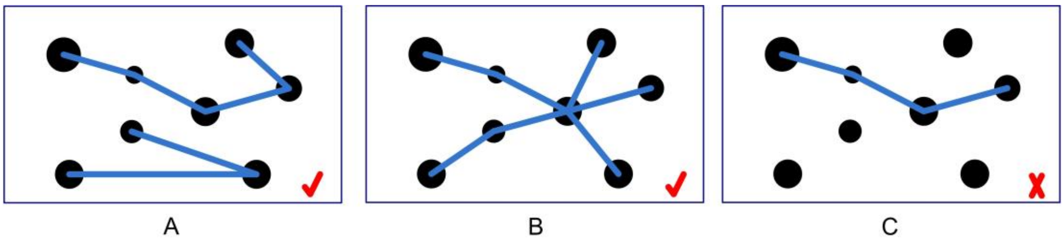

Figure 6.7: Connection examples. Each node must connect to at least one other node. A and B fulfil the connection rule. C does not.

6.4.1.4 Procedure

Participants were divided into random pairs, 12 pairs per condition. Each pair was guided separately into the usability lab (see figure 6.9). Prior to the study, the participants were each provided with a copy of the consent form to sign and filled out a background questionnaire. Any queries relating to the form were answered at this stage. If it was established that participants had never met before, participants were introduced to one another.

The participants were then provided with a copy of the task instructions and asked to read through the instructions as a pair to ensure they were well understood (see Appendices D.1, D.2). The experimenter then proceeded to read aloud the instructions. The study design was between participants (to prevent task familiarisation) with 3 conditions. In the 'pointing' condition, the participants were provided with only the pointing interaction technique (see Figure 6.3 and 6.4b). In the 'scaling' condition, participants were provided with only the scaling interaction technique (see Figure 6.3 and 6.4a-ab). In the 'mixed' condition, participants were provided with both interaction techniques and encouraged to use whichever they preferred at any time.

The participants were sat down initially at a shared desk, presented with the mobile equipment and given training in the use of the mobile media exchange service (both as helper and worker), allowing ample time for familiarisation. During the experiment participants occupied the same usability lab with a divider set up to prevent visual communication by means other than the mobile device provided (see figure 6.8).

Participants were randomly assigned roles (Helper or Worker), and asked to collaboratively complete the puzzle. The Helper was provided with diagrammatic instruction in both printed form and visually on the Helper's mobile display containing the final puzzle state, so that the helper could guide the actions of the Worker in completing the 'connect the dots' puzzle. The Worker activities (with no initial knowledge of the final puzzle state) were to receive instructions from the Helper, collaborate through the mobile device and sketch the correct final diagram using the pen and paper materials provided.

In addition, Workers were instructed that they were not allowed to see the Helper's instructions. Both participants were instructed that they could talk at all times, were provided a maximum of 10 minutes to complete the task and asked to complete the task as quickly as possible (most pairs completed in less than 5 minutes). Post task completion, the participants provided subjective feedback on the condition just used and completed a NASA TLX workload assessment (see Appendices D.5-D.7).

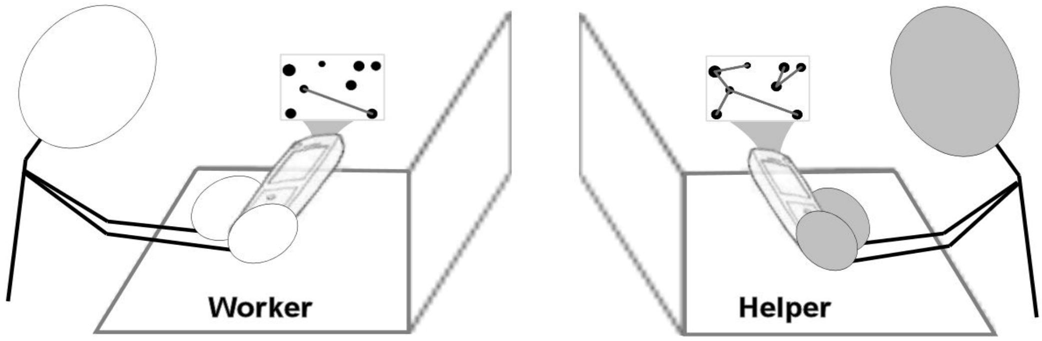

Figure 6.8. Collaborative study Helper/Worker set-up.

6.4.1.5 Participants

We ran 72 participants (36 pairs), 24 participants for each of the three conditions. Participants were recruited from undergraduate and postgraduate students at the University of Bath Department of Computer Science. The average participant age was 23; eight participants were female. Post-experiment questionnaires indicate that all participants were well versed in the use of mobile telephony devices, with an average of over four years of mobile phone usage.

Participants were recruited due to their familiarity with existing mobile devices, services (e.g. text messaging and MMS) and willingness to adopt new technologies [Divitini *et al.* 2002], in an effort to reduce possible confounding effects that might arise from the use of mobile devices (input mechanisms and functions) throughout the experiments as opposed to the communication conditions that were being assessed.

There is of course an argument that a broader range of ages and technological familiarity, and more gender balance, would provide a sample more representative of the general population. However a lack of (or significant variation in) familiarity with smart phone technology would introduce confounding factors in a study of this sort. And, despite the best efforts of the telecoms industry, young males remain most likely to have the necessary technophilia.

6.4.1.6 Apparatus

The physical set up of the study was similar to that in Figure 6.8. Each participant was provided with a Smartphone mobile device, a HTC S730s supporting the following specifications: the Windows Mobile 6.1 Standard operating system, a 2.4 inch TFT display with 240x320 pixels and an internal 802.11g wireless module which was used throughout the experiments to establish communication between the devices.

Smartphone (non-touch screen) mobile devices were used throughout the experiments enabling one or two handed input using the directional keypad and the built-in T9 input keys. Each mobile device was pre-loaded with a custom built stand-alone Windows Mobile Photo-Conferencing client (see Chapter 5), that established communication between the two mobile devices, creating a shared visual space in which a number of communication conditions could be utilised.

The application was always run in full screen mode to ensure the only interface displayed and accessible to the user would be the puzzle task. The devices used in the experiment were identical in make and model and both fully charged to eliminate any processor throttling effect on transmission speeds.

The desk chairs provided were height adjustable, each participant's desk was shielded by a tall divider to prevent direct visual communication between participants, and verbal communication was allowed. The experimenter observation desk occupied a separate room adjacent to the participants' room, in which the experiment was monitored and recorded.

The experimenter had access to an Apple Macbook laptop computer [MBPRO 12/2.33/3G/160/SD/MDM/AP/BT GBR] displaying real-time session information and log data for the active experiment to assist with monitoring and observational note taking.

The experiment's progress was monitored by two cameras in the participant's room that fed through a monitor providing a real-time image to the experimenter. Also in the participants' room a MiniDV video camera (Sony Handycam DCR-HC22E) mounted on a height and angle adjustable tripod was used to record the experiments for future analysis.

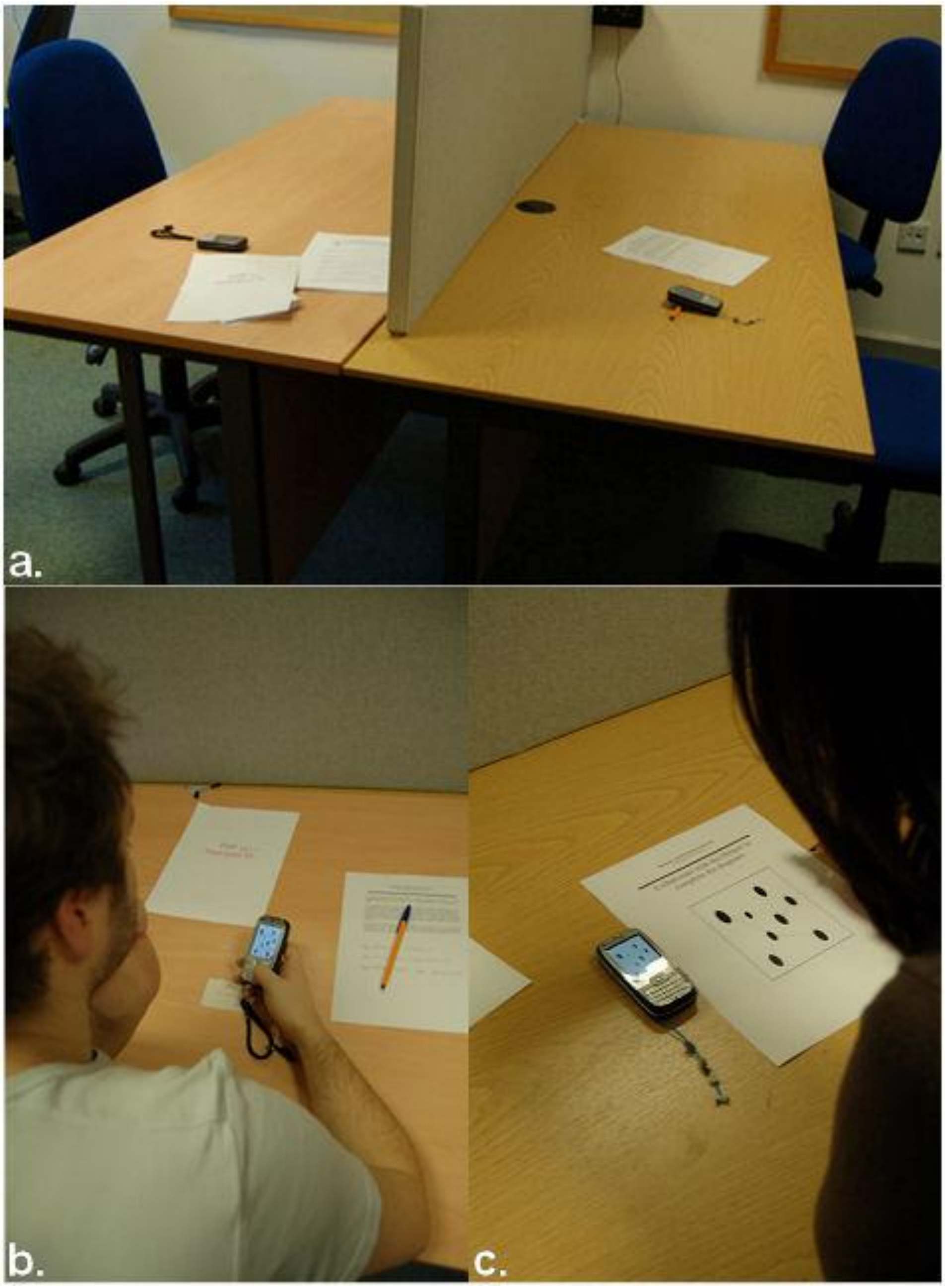

Figure 6.9. Experiment setup with divider to prevent visual communication (a). Participants (bottom row): Helper on the left (b) and Worker on the right (c).

6.4.1.7 Materials

Both participants were each provided with a copy of the instruction sheet that was read out prior to commencing the experiment (see Appendix D.1) and provided on a single side of A4 paper on the participants' desks for further reference. An additional copy was also used by the experimenter. The Helper was also provided with a copy of the final puzzle diagram and a mobile key-pad reference diagram (see Appendix D.4 and Figure 6.1.5) to provide a quick reference and reminder to the input keys used for the particular experiment, pointing, scaling or mixed. The worker was provided with a copy of the unfinished puzzle diagram (see Appendix D.3) and a pen to draw in the relevant diagram.

In addition to task based material, participants were also provided with A4 paper consent forms to sign, questionnaire materials including NASA TLX for subjective assessment of mental workloads (including both the subscales and the paired-comparisons forms) and a bespoke evaluation questionnaire (see Appendices D.5-D.9).

6.4.1.8 Problems encountered

No major task completion problems were encountered. Some entry errors were observed, e.g. a mis-pressed button during a selection or a transmission procedure. As such entry errors are part of standard mobile use, these input errors were allowed.

Mobile phone based recording software was initially used in pilot studies, but the performance impact was found to be inconsistent and was removed because the inability to precisely control and measure its overall impact on the task performance outweighed its usefulness. Instead, server side (pass through) logging software was used, in which each transmitted command was logged.

During one of the experiments, WiFi connectivity (supplied by the university) was lost due to a minor outage. Although this didn't directly impact the system which resumed after the outage, task completion time (a measurable result) was affected and these results were removed.

6.4.2 Statistical Analysis

We compared a range of performance measurements across the three conditions, including task completion time, number of words used by the participants, number of key-presses, error rates, and a measure of cognitive workload.

6.4.2.1 Task completion time

The mean task completion time for each condition is presented in Table 6.1 (first row). A one-way ANOVA across the three conditions found a significant effect on task completion time ($f_{2,33} = 14.172$, $p \leq .002$). Post hoc pairwise two-tailed, independent t-tests found a significant difference between pointing and scaling ($t_{22} = 5.53$, $p \leq .05$), and between the scaling and mixed conditions ($t_{22} = -4.91$, $p \leq .005$). No significant difference was found between the pointing and mixed conditions ($t_{22} = 0.23$, n.s.).

Table 6.1: Mean (and SDs in parentheses) performance of collaborating pairs across conditions (Time: in seconds, Errors: average per experiment).

	Pointing	Scaling	Mixed
Time	141.00 (41.4)	71.08 (14.12)	140.58 (46.92)
Errors	0.33 (.49)	0.25 (.45)	0.17 (.39)

The pointing and mixed conditions produced almost identical completion time results (see Table 6.1, first row). A bivariate analysis found strong linear correlation between the pointing and mixed conditions ($p \geq .81$). This may be attributed to participant's preferential use of pointing rather than scaling at a ratio of 63:37 in the mixed condition. Log records indicate that most participants were experimental in their interaction choice and on average alternated between pointing and scaling up to five times during a typical session even though they preferred pointing interactions.

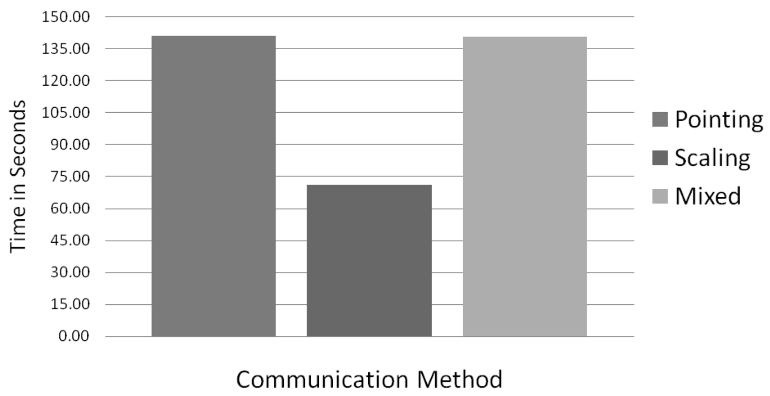

Figure 6.10: Mean task completion time, in seconds across conditions.

Results for task completion time indicate that the scaling only condition (see Figure 6.10) enabled participants to complete the task in approximately half the time of the pointing and mixed conditions.

6.4.2.2 Error Rates

We performed post-trial analyses of error rates (Table 6.1, bottom row). Error rates are a representation of the number of incorrectly connected nodes from each "connect the dots" puzzle task. A one-way ANOVA across the three conditions found no significant effect on the number of errors made across conditions ($f_{2,33} = .41$, n.s.).

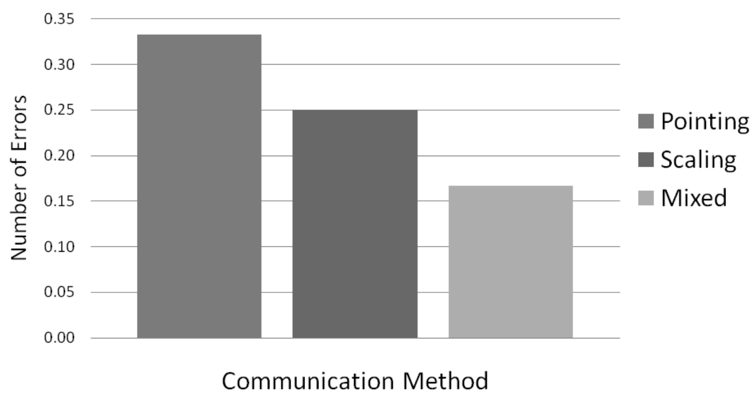

Figure 6.11: Mean number of error rates across conditions.

Although the error rates suggest that a mixed condition could lead to 50% reduction (see Figure 6.11) in error rates compared to the pointing only condition, no significant difference was found, perhaps due to the overall low error count.

6.4.2.3 Conversation Analysis

The number of words used by the participants was taken as a measure of task workload. Transcripts were created from video recordings of the experimental trials and the total number of words used by each Helper/Worker pair was calculated for each session (see Figure 6.12). The mean number of words used by the pairs in each condition is presented in Table 6.2.

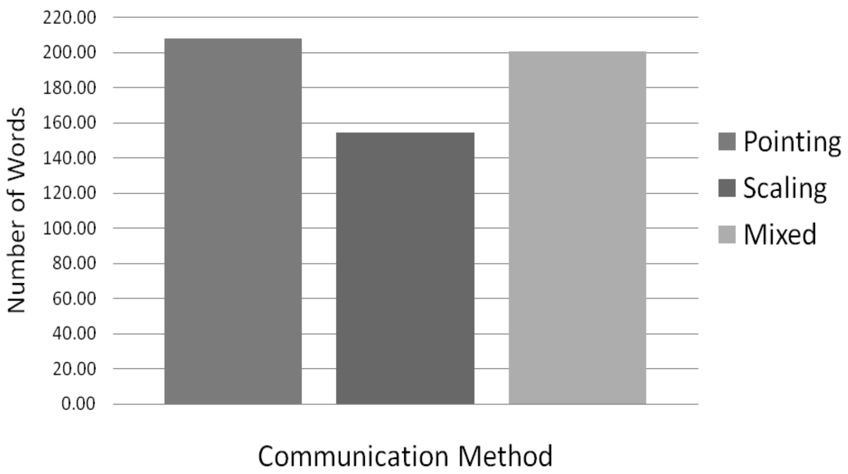

Figure 6.12: Mean number of words spoken across conditions.

Table 6.2: Mean (and SDs in parentheses) performance of collaborating pairs across conditions (Words: number of words).

	Pointing	Scaling	Mixed
Words	208.08 (61.87)	154.58 (38.27)	200.58 (39.16)

A one-way ANOVA found a significant difference in the number of words used across the conditions ($f_{2,33} = 4.42$, $p \leq .02$). Post hoc pairwise two-tailed, independent measures t-tests found significant differences between pointing and scaling ($t_{22} = 2.54$, $p \leq .02$), and between the scaling and mixed conditions ($t_{22} = -2.91$, $p \leq .02$). No significant difference was found between the pointing and mixed conditions ($t_{22} = .35$, n.s.).

In addition to this quantitative analysis of the participants' dialogues, we performed an informal analysis of participant comments. Comparing the pointing and scaling methods, we observe that whereas in the pointing excerpt the Worker is obliged to verify every single Helper instruction, with each object being identified and clarified one at a time, in the scaling condition the Helper is more directive, with many objects being identified at the same time, with the Worker not needing to respond to every action.

Users of scaling tended to adopt a 'relative referencing' approach in which multiple onscreen objects were identified en bloc with no intervening backchannel, e.g. "The three ones at the top are connected and that's the top one with the left one and the middle left one with the right middle one.". In contrast, users of pointing adopted a 'precision referencing' approach of identifying each object one at a time sequentially "This one is the first one (.) connect it with this one", despite their ability to utilise relative referencing in which pointing at a single object could have been used to identify surrounding objects.

6.4.2.4 Event Analysis

Event-logs recorded during the experimental trials provided data on the number of key-presses utilised during each trial (see Figure 6.13). The data were collected using the photo-conferencing service's built-in event logger, which was active throughout all sessions. The results of the event-log can be seen in Table 6.3 (first row).

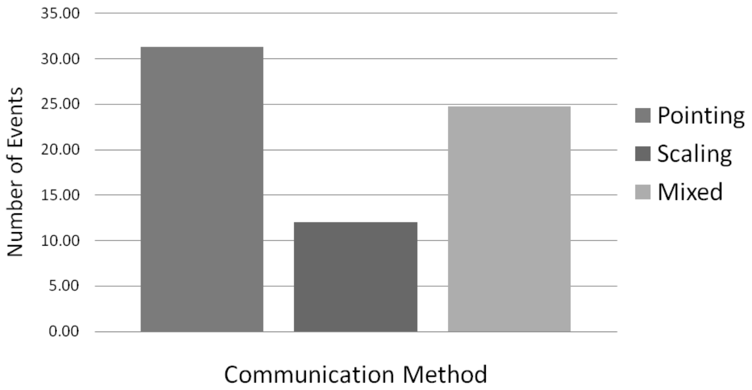

Figure 6.13: Mean number of key presses across conditions.

A one-way ANOVA across the three conditions found a significant effect on the number of key-presses required to complete the task ($f_{2,33} = 14.44$, $p \leq .002$). Post hoc pairwise two-tailed, independent measures t-tests found a significant difference between pointing and scaling ($t_{22} = 5.73$, $p \leq .002$), and between the scaling and mixed conditions ($t_{22} = -3.85$, $p \leq .001$). No significant difference was found between the pointing and mixed conditions ($t_{22} = 1.55$, n.s.).

Table 6.3: Mean (and SDs in parentheses) performance of collaborating pairs across conditions (Events: number of key presses, Workload: NASA TLX).

	Pointing	Scaling	Mixed
Events	31.33 (10.47)	12.00 (5.15)	24.75 (10.23)

6.4.2.5 Workload Analysis

Post-trial analyses of mental workload were performed by administering the NASA TLX using both sections of the assessment, the sub-group scales and the paired comparisons section. This weighted measure gave a score out of 20 (see Table 6.4, Figure 6.14), with 20 representing the highest possible level of mental workload. For completeness [Byers *et al.* 1989] unweighted measures are also presented; see Figure 6.15.

A one-way ANOVA across the three conditions for each sub-scale found a significant effect on temporal demand ($f_{2,33} = 7.45$, $p \leq .002$), with no significant effect on mental demand ($f_{2,33} = 2.51$, n.s.), physical demand ($f_{2,33} = .85$, n.s.), performance ($f_{2,33} = 1.32$, n.s.), effort ($f_{2,33} = .29$, n.s.) or frustration ($f_{2,33} = 2.41$, n.s.). Post hoc pairwise two-tailed, independent measures t-tests found a significant difference in temporal demand between pointing and scaling ($t_{22} = -34.9$, $p \leq .005$), and between scaling and mixed ($t_{22} = 3.94$, $p \leq .005$). No significant difference was found between the pointing and mixed conditions ($t_{22} = -.68$, n.s.).

These results indicate a higher perceived temporal demand for scaling in comparison to pointing, contradicting to some extent our findings on task completion times (see Table 6.1, first row).

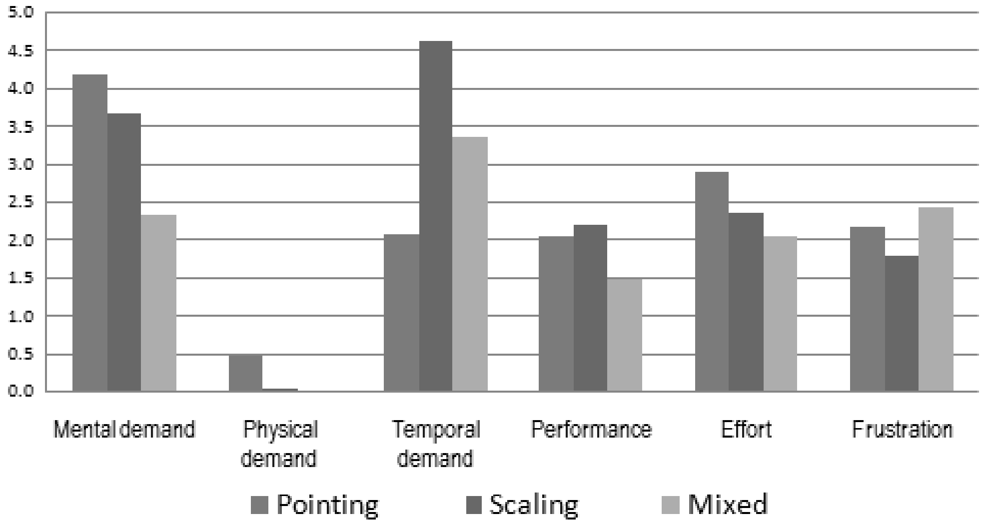

Figure 6.14. Workload: Mean weighted (NASA TLX both sections) mental workload sub-scales across conditions.

Table 6.4: Workload: Mean weighted (NASA TLX both sections) mental workload sub-scales across conditions: Pointing, Scaling and Mixed. SDs in parentheses.

	Pointing	Scaling	Mixed
Mental demand	4.19	3.68	2.36
	(1.55)	(2.76)	(2.09)
Physical demand	0.48	0.06	0.00
	(.57)	(.03)	(.)
Temporal demand	2.08	4.63	3.38
	(1.32)	(1.09)	(1.85)
Performance	2.07	2.22	1.51
	(1.72)	(.93)	(.3)
Effort	2.91	2.37	2.05
	(1.94)	(1.56)	(1.75)
Frustration	2.19	1.80	2.46
	(1.91)	(1.18)	(1.65)

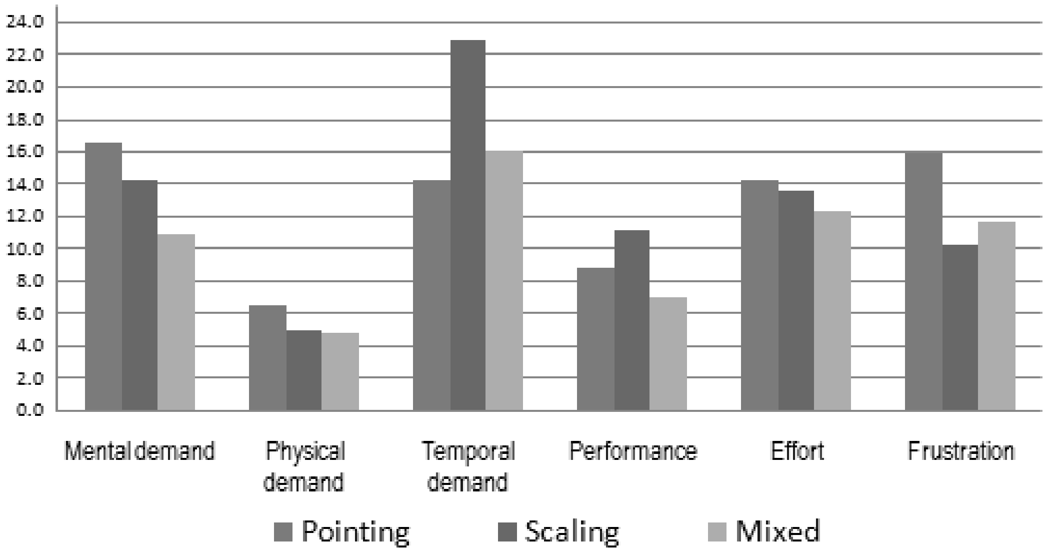

Figure 6.15. Workload: Mean unweighted (NASA TLX first section only) mental workload sub-scales.

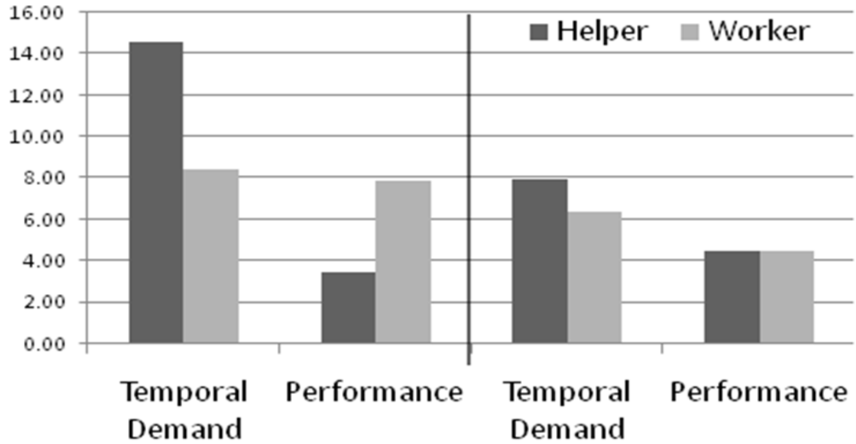

Figure 6.16. Scaling (left), Pointing (right) Helper/Worker un-weighted mental workload sub-scales comparison.

Further analysis of participant workload compared helper/worker pairs in the scaling and pointing condition (see Figure 6.16, 6.17). Differences indicate that the higher temporal demand was perceived primarily by the helper. A post hoc pairwise two-tailed, repeated measures t-test found significant difference in temporal demand ($t_{24} = 9.17$, $p \leq .002$) and performance ($t_{24} = -2.6$, $p \leq .05$), in the scaling only condition.

The results also indicate the contradiction between helper/worker pairs in the scaling only condition, by which helpers in the scaling only condition perceived a negative impact: higher temporal demand and reduced performance (see Figure 6.18). However, the accompanying workers perceived a positive impact: significantly lower temporal demand (see Figure 6.18 Temporal demand) and improved performance (see Figure 6.18 Performance) in the same task. This is in contrast to the pointing only condition in which helper/worker pairs shared similar perceptions of task performance (see Figure 6.17 Performance).

From the results in the pointing only and mixed conditions we can observe on average, both helper and workers pairs perceived similar workloads (see Figure 6.17, 6.19). However, in the scaling only condition helper and workers pairs have more varying perceptions (see Figure 6.18).

Finally, a finding consistent across all conditions is that the helper always perceived a higher temporal demand than the worker, which may be attributed to the nature of the task in which the helper is responsible for guiding the actions of the worker to ensure the task is completed as quickly as possible.

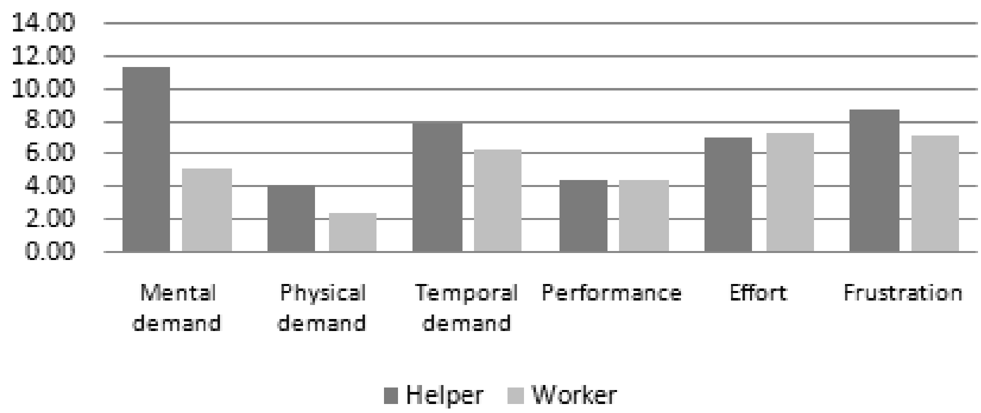

Figure 6.17. Workload: Mean 'Pointing' unweighted Helper/ Worker workload sub-scales comparison.

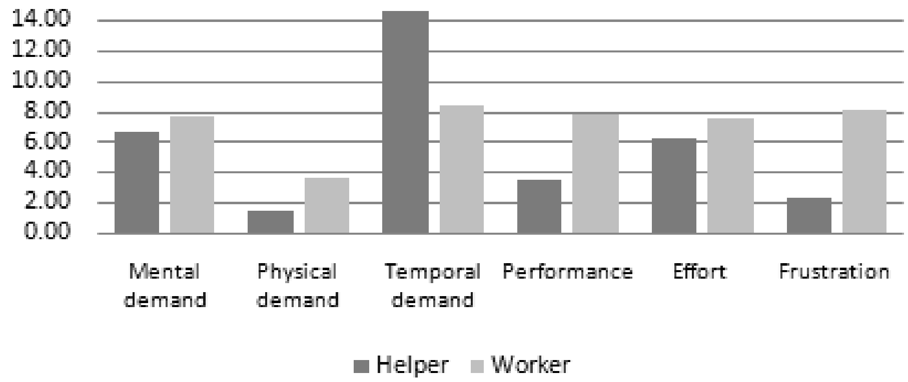

Figure 6.18. Workload: Mean 'Scaling' unweighted Helper/ Worker workload sub-scales comparison.

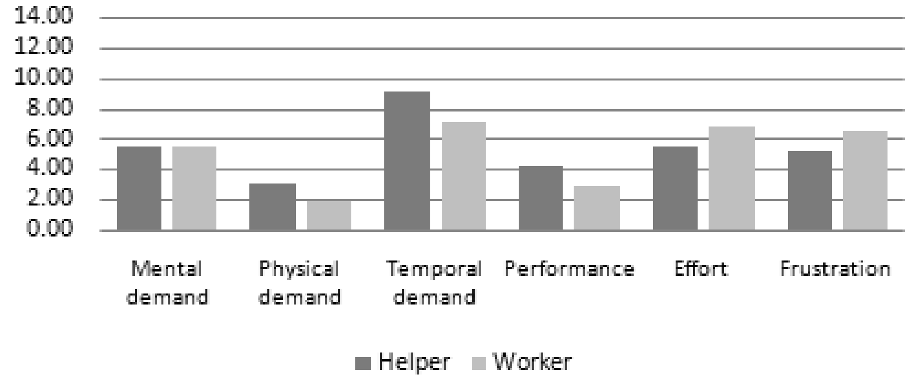

Figure 6.19. Workload: Mean 'Mixed' unweighted Helper/ Worker workload sub-scales comparison.

6.4.3 Subjective Feedback

Participants' qualitative feedback was collected through a 6-point Likert scale gauging mobile phone experience (based on number of phone calls they make, use of the camera phone facilities, text messaging and multimedia messaging services during a typical day) and a questionnaire on the condition they had just used, see Appendix D.8-D.9.

An interesting finding with respect to the logged data was found in the scaling only feedback. When asked "what feature if added would enhance the collaborative performance?", many participants indicated their desire for a cursor as a precision pointing mechanism in addition to the scaling mechanism provided.

6.4.4 Discussion

The scaling only condition enabled participants to complete the task in almost half the time of the pointing only and the mixed conditions. This finding suggests that the use of scaling can accelerate the process of achieving conversational grounding [Clark and Wilkes-Gibbs 1986] in this kind of mobile collaborative setting. According to the principle of least collaborative effort [Clark and Wilkes-Gibbs 1986], people should try to ground with as little combined effort as possible and change their communicative strategies based on certain costs of the communication medium [Clark and Brennan 1991].

With scaling only we observed a reduction in combined frustration taking place (Table 6.5, sixth row). These results are corroborated by findings in the event analysis that show far fewer interaction events are required when using scaling in comparison to the pointing and mixed conditions (Table 6.4).

However, a side effect of scaling only can be seen in the subscale comparison of mental workload, in which a much higher temporal demand (Table 6.5, third row) indicated that participants *perceived* that faster results could have been possible, despite completing the task in almost half the time of the pointing only and mixed conditions (Table 6.1, first row). This contradiction between user's perception and measured results highlights the importance in studies of this nature of collecting both quantitative and qualitative feedback to completely understand the user's experience.

Additionally in their post-trial feedback, users in the scaling only condition – where no pointer was present – explicitly requested a pointing "cursor" as a means to simplify performance of the task. The high proportion of pointing used in comparison to scaling (63:37) in the mixed condition supports the suggestion that, given a choice of pointing or scaling, users prefer pointing.

Our informal analysis indicates that the relative referencing afforded by the scaling method can better support remote mobile media exchange, accelerating grounding and supporting the principle of least collaborative effort. Although participants preferred the precision referencing afforded by a pointer, the combination of relative referencing with precision referencing in the 'mixed' condition did little to enhance performance, faring only slightly better than the pointing only condition and much worse than the scaling only condition (see Table 6.1).

Though the users' expressed desire for precision pointing may be attributable simply to first time use of the system after long experience with pointer-based interfaces, or its similarity to the real world physical interaction of pointing with one's finger that is also observed in studies of remote virtual interactions [Robertson 2000], it does highlight the need to take into account familiar input mechanisms when designing for usability of remote mobile interactions.

Finally, the initial hypothesis [H1] was not supported, as the mixed condition did not offer the best of both worlds as we had predicted, but saw most users going with their preference for pointing, contributing to the strong correlation between the mixed and pointing results.

6.5 Study 2 – Hybrid Technique

In this second study we drew on the most successful characteristics (derived from relative referencing 'scaling' and precision pointing 'pointing') found in our first study to design a new 'Hybrid' interaction technique. The new interaction combines in one technique relative and precision referencing to further enhance performance and attempt to further reduce task effort [Clark and Wilkes-Gibbs 1986].

In further experimental evaluations we used this 'Hybrid' condition to test a second hypothesis based on our findings from the first study, reported above:

> *[H2] An enhancement to the relative referencing interaction provided by the scaling mechanism and the integration of a complementary precision referencing facility (rather than simple juxtaposition of pointing and scaling techniques) would further improve the mobile collaborative performance measurements (task completion time, number of words used by the participants, number of key-presses, error rates and measure of cognitive workload), minimising collaborative effort [Clark and Wilkes-Gibbs 1986].*

6.5.1 Study Methodology

6.5.1.1 Design

The experiment builds on Study 1 and introduces a new independent variable to the between participants design. The original study manipulated one independent variable, communication method, consisting of the original three levels, 'pointing', 'scaling' and 'mixed' accompanied by an audio channel. Here we present a new fourth 'hybrid' interaction technique that is also accompanied by an audio channel. In the new 'hybrid' condition, the participants are provided with only the hybrid facility of the mobile photo-conferencing service.

6.5.1.2 Hybrid Interaction Technique

A new interface was constructed for the hybrid condition (see Figures 6.22 and 6.23ca-cb) that was motivated by our earlier findings and informal participant comments. The new interface combines the characteristics of relative and precision referencing to form a new coherent design that attempts to further reduce task workload.

The 'hybrid' design incorporates H2 through a grid layout that divides up the screen space with semi-transparent visible segmentation (grid lines), providing a co-ordinate reference scheme (regions 1-9) and the ability to scale through selection to further enhance relative referencing and instantly reduce the available search space, similar to the scaling condition's facility to drill down to a specific view. Precision referencing was also integrated through the use of a pointing mechanism, consisting of a semi-transparent red-highlight selection area (see Figures 6.22 and 6.23ca-cb). This pointer is locked to the relative referencing grid, indicating areas of immediate focus and also enabling relative referencing of surrounding areas.

Figure 6.20. Picture which does not use the rule of third (left), Picture that use the rule of thirds (right).

Figure 6.21. Scene framing and alignment grid, a common feature on most digital cameras.

A 3x3 grid segmentation was used (as opposed to a 2x2 or 5x5 grid etc) to provide a similar coverage area to the pointer based interaction and to draw on familiar characteristics adopted by consumer digital photography products (see Figure 6.21) and techniques such as the rule of third (see Figure 6.20).

The rule of thirds is an important aspect of photographic composition [Houston 2000]. It is a guideline to create a well balanced picture and has also been used by painters for centuries. Based on this rule the centre part of a given picture is not the best place for the eye, so to apply this rule, users imagine the camera's view finder is etched with grid lines (see Figure 6.20, 6.21) and the subject is placed at the intersection of the grid lines. By using this method, it is easier to compose a well balanced picture (see Figure 6.20 Right).

Our hybrid interaction technique approach draws on already established photography techniques to facilitate both relative and precision referencing, whilst maintaining minimal on-screen clutter from excessive grid lines that could overwhelm a mobile device's small display. With this approach relative and precision mechanisms can facilitate the hybrid interaction and provide the means by which participants can coordinate language, maintain a common vocabulary, e.g. "top left" or "grid number 3", and establish common ground in an attempt to reduce overall collaborative effort [Kraut, et al. 2002].

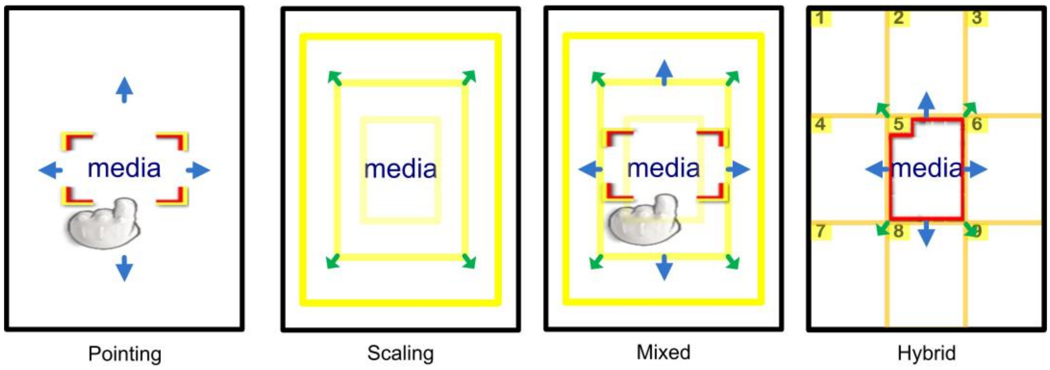

Figure 6.22. Pointing, Scaling, Mixed and Hybrid interaction conditions. Blue arrows indicate panning actions and green arrows indicate scaling action.

(ca) (cb)

Figure 6.23. Hybrid interface (ca); Hybrid interface after 1 degree of scaling (cb).

6.5.1.3 Interaction Technique

In the hybrid interaction technique, keypad input is performed using a combination of six buttons: the directional-pad (up, down, left, right) for co-ordinate selection, the enter-button to scale into the selected co-ordinate area and the back-button to scale out of the selected co-ordinate area. The animation speed at which all actions occur on user input was set to 500 milliseconds from start to finish due to processor limitations. Any event occurring on one device's screen made the same event occur synchronously on the other device's screen.

6.5.1.4 Experimental Task

Study 2 repeated the puzzle based task paradigm which required a Helper to guide the actions of a Worker in the completion of a "connect the dots" diagram.

Figure 6.24. Experiment setup/participants, Helpers on the left and Workers on the right.

6.5.1.5 Procedure

Participants were divided into random pairs, 8 pairs in total. Each pair was guided separately into the usability lab (see figure 6.24). Prior to the study, the participants were each provided with a copy of the consent form to sign and filled out a background questionnaire. Any queries relating to the form were answered at this stage. If it was established that participants had never met before, participants were introduced to one another.

Participants were then provided with a copy of the task instructions and asked to read through the instructions as a pair to ensure they were well understood (see Appendix D.1). The experimenter then proceeded to read aloud the instructions.

The study repeated the puzzle based task paradigm which required a Helper to guide the actions of a Worker in the completion of a "connect the dots" diagram. The procedure was identical to that of the previous study but participants were provided with only the hybrid interaction technique (see Figures 6.23 and 6.22ca-cb).

6.5.1.6 Participants

We ran a group of 16 participants (8 pairs, not used in Study 1), again recruited from undergraduate and postgraduate students at the University of Bath. The average age of participants was 25, four participants were female, and all participants were well versed in the use of mobile devices with an average of over four years' mobile phone use.

6.5.1.7 Apparatus

The apparatus was identical to the first study and the same mobile devices and study setup were used to enable direct comparison. In this hybrid interaction technique condition, keypad input is performed using a combination of six buttons: the directional-pad (up, down, left, right) for co-ordinate selection, the enter-button to scale into the viewable co-ordinate area and the back-button to scale out of the viewable co-ordinate area. Any event occurring on one device's screen made the same event occur synchronously on the other device's screen.

We recorded a range of performance measurements, including task completion time, number of words used by the participants, number of key-presses, error rates, and a measure of cognitive workload.

6.5.1.8 Materials

Both participants were each provided with a copy of the instruction sheet that was read out prior to commencing the experiment on a single side of A4 (see Appendix D.1) and provided on participants desks for further reference. An additional copy was also used by the experimenter. The Helper was also provided with a copy of the final puzzle diagram to create expert status and a mobile key-pad reference diagram (see Appendix D.4 and Figure 6.1.5) to provide a quick reference and reminder to the input keys used for the hybrid experiment. The worker was provided with a copy of the unfinished puzzle diagram (see Appendix D.3) and a pen to draw the relevant diagram.

In addition to task based materials, participants were also provided with A4 paper consent forms to sign, questionnaire materials including NASA TLX for subjective assessment of mental workloads (including both the subscales and the paired-comparisons forms) and a bespoke evaluation questionnaire (see Appendices D.5-C9).

6.5.1.9 Problems encountered

No major task completion problems were encountered. Some entry errors were observed, e.g. a mis-pressed button during a selection or a transmission procedure. As such entry errors are part of standard mobile use, these input errors were allowed.

6.5.2 Statistical Analysis

We analysed a range of performance measurements, including task completion time, number of words used by the participants, number of key-presses, error rates, and a measure of cognitive workload. Results from this study of the hybrid interaction technique were compared with these results from the pointing, scaling and mixed conditions evaluated in Study 1.

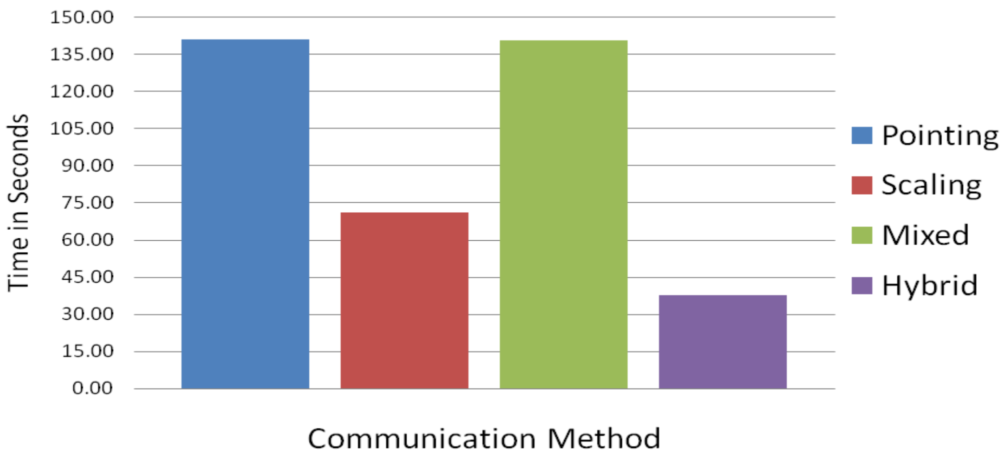

Figure 6.25: Mean task completion time, in seconds across conditions.

6.5.2.1 Task completion time

We performed the same analysis as in our first study, accounting for the lower number of participants (harmonic mean statistical methods provides by the SPSS v16 statistical package) in the new, fourth condition provided by the hybrid interaction technique. Table 6.6 (first row, fourth column) shows the timing results. A one-way ANOVA across the hybrid and the previous three conditions (pointing, scaling, mixed) found a significant effect on task completion time ($f_{3,40} = 18.31$, $p \leq .002$). Mean comparison (see Table 6.5: top row) suggested that the hybrid was almost twice as fast as the scaling only condition, with post hoc pairwise two-tailed, independent t-tests indicating a significant difference between hybrid and scaling ($t_{18} = 2.46$, $p \leq .05$).

These results indicate that in terms of completion time, an integrated combination of relative referencing and precision referencing can lead to improved measurements compared to pointing only (see Figure 6.25), the simple offering of both pointing and scaling in the mixed condition, and to the previously best performing scaling only condition.

Table 6.5: Mean (and SDs in parentheses) performance of collaborating pairs across conditions (Time: in seconds, Errors: average per experiment).

	Pointing	Scaling	Mixed	Hybrid
Time	141.00 (41.4)	71.08 (14.12)	140.58 (46.92)	37.58 (11.26)
Errors	0.33 (.49)	0.25 (.45)	0.17 (.39)	0 (0)

6.5.2.2 Error Rates

Error rates were calculated based on the same kind of analysis as in study 1. There were no errors in the hybrid condition (see Table 6.5, second row, forth column). A one-way ANOVA across the hybrid and three previous conditions found no significant effect on the number of errors made ($f_{3,40} = 1.16$, n.s.), probably due to the overall low error rates (see Figure 6.26).

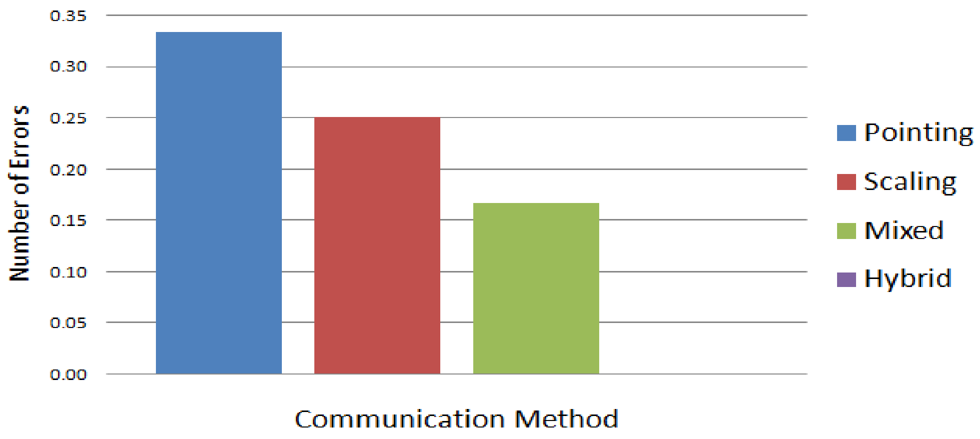

Figure 6.26: Mean number of error rates across conditions.

6.5.2.3 Conversation Analysis

The mean number of words used by the pairs in each condition is presented in Table 6.6 (third row, fourth column). A one-way ANOVA found a significant difference between the number of words used across the hybrid and three previous conditions ($f_{3,40}$ = 12.28, p ≤ .002).

Table 6.6: Mean (and SDs in parentheses) performance of collaborating pairs across conditions (Words: number of words).

	Pointing	Scaling	Mixed	Hybrid
Words	208.08 (61.87)	154.58 (38.27)	200.58 (39.16)	98.75 (20.85)

A post hoc pairwise two-tailed, independent measures t-test comparison against scaling (the most effective interaction in our previous study) found a significant difference between hybrid and scaling (t_{18} = 3.7, p ≤ .001), with the mean word counts indicating better performance in the hybrid condition (see Figure 6.27), again supporting H2.

From informal analysis of participant comments we observed a variation of relative referencing, "the dot that is between 2 and 5", and precision referencing, "this one", taking place in the hybrid interaction. Although this is somewhat similar to observations from the mixed condition, a much higher proportion (82:12) of relative referencing occurred in the hybrid condition.

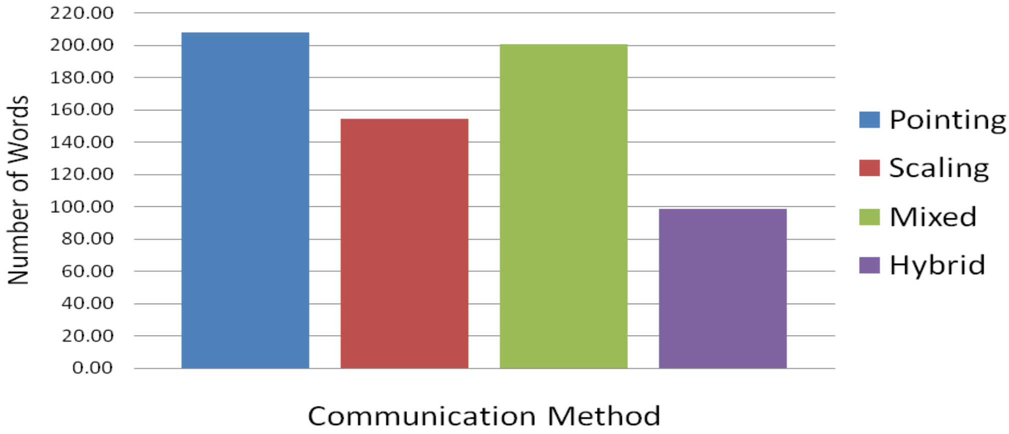

Figure 6.27: Mean number of words spoken across conditions.

6.5.2.4 Event Analysis

Event logs were recorded in the same manner as study 1 and can be seen in Table 6.7. A one-way ANOVA across the four conditions found a significant effect on the number of key-presses required to complete the task ($f_{3,40} = 20.22$, $p \leq .002$). Post hoc pairwise two-tailed independent measures t-tests found a significant difference in the number of key-press events in the hybrid condition compared to the scaling only condition ($t_{18} = 3.1$, $p \leq .006$), with the mean scores indicating better performance in the hybrid condition, again supporting H2.

The results also suggested a significant reduction in key-presses in the hybrid condition compared to the mixed condition (see Figure 6.28) in which pointing was chosen over scaling by a ratio of 63:37.

Table 6.7: Mean (and SDs in parentheses) performance of collaborating pairs across conditions (Events: number of key presses).

	Pointing	Scaling	Mixed	Hybrid
Events	31.33 (10.47)	12.00 (5.15)	24.75 (10.23)	6.00 (3.42)

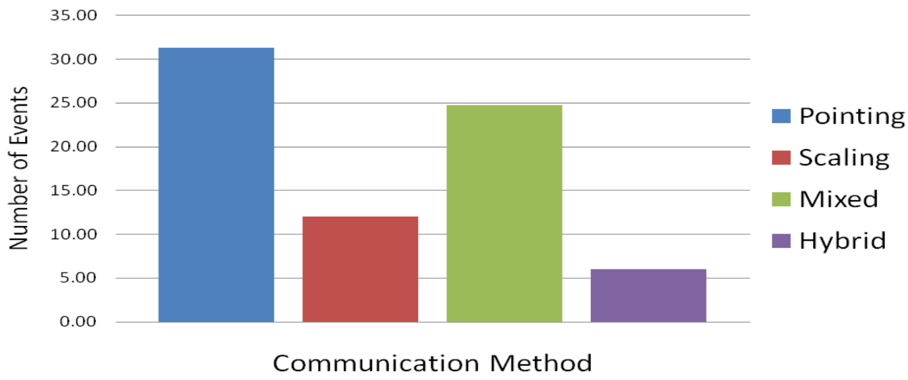

Figure 6.28: Mean number of key presses across conditions.

6.5.2.5 Workload Analyses

Post-trial analysis of mental workload was again performed by administering the NASA TLX as in the previous study. Weighted results are presented in Table 6.8 (fourth column) and Figure 6.29. For completeness [Byers, et al. 1989], unweighted measures are also presented; see Figure 6.30.

A one-way ANOVA for each sub-scale across the four conditions found a significant effect on mental demand ($f_{3,40} = 3.6$, $p \leq .02$), temporal demand ($f_{3,40} = 8.20$, $p \leq .001$), performance ($f_{3,40} = 3.67$, $p \leq .02$) and frustration ($f_{3,40} = 3.51$, $p \leq .02$). No significant difference was found in physical demand ($f_{3,40} = .98$, n.s.) or effort ($f_{3,40} = .82$, n.s.). A post hoc pairwise two-tailed, independent measures t-test comparison of hybrid against scaling only (the most effective interaction in study 1) found a significant difference in mental demand ($t_{18} = 2.06$, $p \leq .05$), temporal demand ($t_{18} = 7.3$, $p \leq .005$) and performance ($t_{18} = 3.5$, $p \leq .005$). But no significant difference was found in frustration ($t_{18} = 1.54$, n.s.).

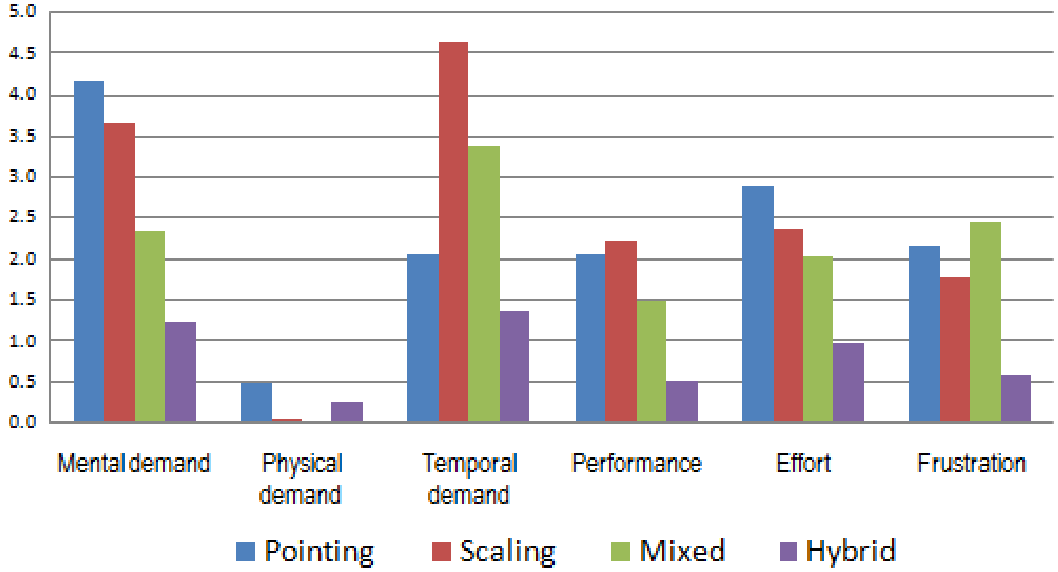

Figure 6.29. Workload: Mean weighted (NASA TLX both sections) mental workload sub-scales across communication conditions: Pointing, Scaling, Mixed and Hybrid.

Table 6.8: Workload: Mean weighted (NASA TLX both sections) mental workload sub-scales across conditions: Pointing, Scaling and Mixed. SDs in parentheses.

	Pointing	Scaling	Mixed	Hybrid
Mental demand	4.19 (1.55)	3.68 (2.76)	2.36 (2.09)	1.25 (1.62)
Physical demand	0.48 (.57)	0.06 (.03)	0.00 (.)	0.25 (.39)
Temporal demand	2.08 (1.32)	4.63 (1.09)	3.38 (1.85)	1.37 (1.36)
Performance	2.07 (1.72)	2.22 (.93)	1.51 (.3)	0.51 (.54)
Effort	2.91 (1.94)	2.37 (1.56)	2.05 (1.75)	0.99 (.91)
Frustration	2.19 (1.91)	1.80 (1.18)	2.46 (1.65)	0.58 (.5)

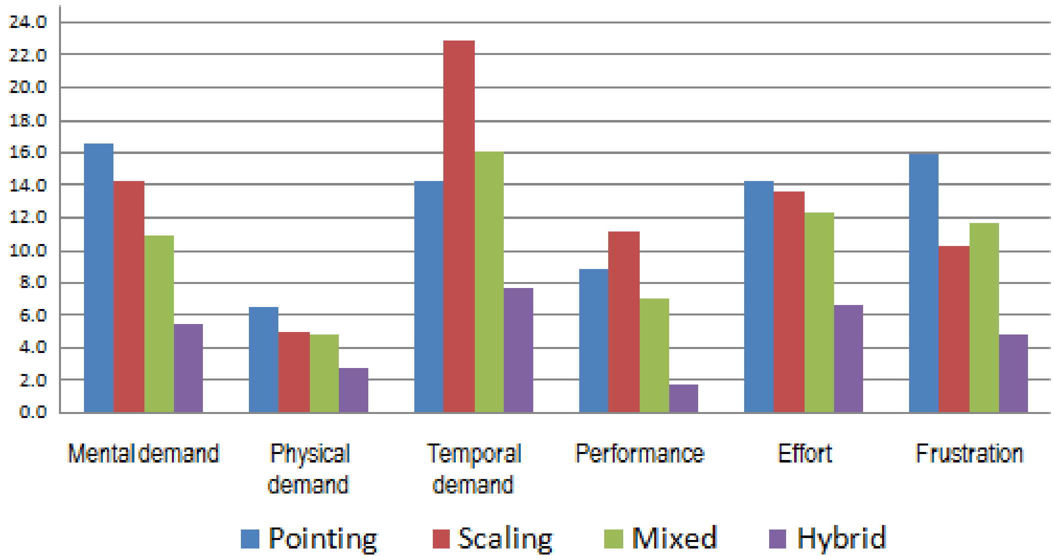

Figure 6.30. Workload: Mean unweighted (NASA TLX first section only) mental workload sub-scales across communication conditions: Pointing, Scaling, Mixed and Hybrid.

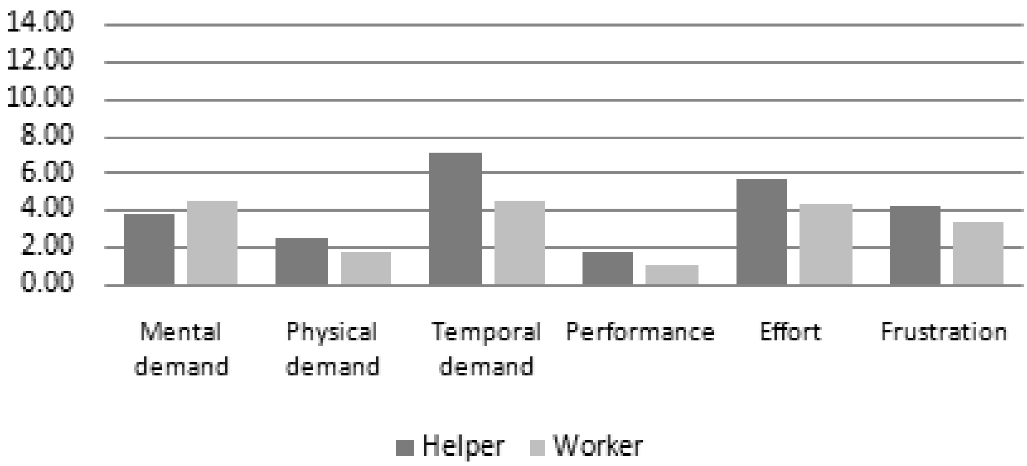

Figure 6.31. Workload: Mean 'hybrid' unweighted Helper/ Worker workload sub-scales comparison.

In comparison to the findings from Study 1, in which the actual and perceived performances of the scaling only condition differed (fastest in Study 1, see Figure 6.18), we can observe that the hybrid condition on average, both helper and workers pairs perceived similar workloads (see Figure 6.31). Additionally, a finding consistent across all conditions in the previous study and also in the hybrid condition is that the helper always perceives a higher temporal demand than the worker. This may be attributed to the nature of the task in which the helper is responsible for guiding the actions of the worker to ensure the task is completed as quickly as possible.

6.5.3 Subjective Feedback

Qualitative feedback was collected in an identical method to Study 1, see Appendix D.8-D.9. When asked "what feature if added would enhance the collaborative performance?" no common response was provided, with most participants indicating positive satisfaction with the hybrid interaction condition.

6.5.4 Discussion

Although our initial hypothesis (H1) reflected an assumption that more is better, i.e. providing both scaling and pointing interaction techniques would enhance usability, the actual effects have proved more subtle. Offering the two together in the first study certainly wasn't more useful than providing one or the other alone. However, the new hybrid interaction technique that we developed to offer an integration of the best features of each technique led to significant gains, as predicted in H2.

The 'Hybrid' results showed a significant reduction, compared to the scaling only, pointing only and mixed conditions, in users' overall collaborative effort [Clark and Brennan 1991] as measured by task completion times, conversation, event and workload required to complete the shared task.

The hybrid condition saw an increase in the ratio of relative referencing (of surrounding items) to precision referencing (pointing with an area box) compared to our findings for the mixed condition, corroborating earlier findings from the scaling only condition in which an increased use of relative referencing saw a significant reduction in the amount of backchannel that took place and accelerated the process of conversational grounding, with the nonverbal communication interactions helping to provide the context for the spoken communication [Tan 1992]. An observation relating to the low error rates across conditions (cf. Table 6.6) suggests that when the probability of referential ambiguity is high, additional costs such as time, number of words spoken or alternative techniques are used to reduce the ambiguity.

The hybrid condition also enhanced users' perception of workload, providing participants with a more realistic perception of task completion time (low temporal demand), and performance perceptions (see Figure 6.31 Performance) that were more in line with actual measured performance results. This is in contrast to our findings from the scaling only condition in which perceived (subjective) and actual performance results contradicted each other.

6.6 Study 3 – Field-Based Observations

Experiments by their very nature are tightly constrained in order to evaluate specific attributes of an environment or interaction technique and have varying ecological validity. Field-based or observational studies are a useful complement to the more straitened studies of the kind reported in the preceding sections of this chapter.

To better understand the issues associated with the mobile media exchange we performed field-based observations and interviews. The aim of these field-based observations was to capture rich contextual information regarding the use of mobile media exchange environments to further gauge end user feedback, reactions and criticisms of such MEA services in a more natural (non-lab based) setting. The field-based observation presented the MEA photo-conferencing instantiation to a broader audience, removing previous lab based constraints and allowing users to explore all aspects of the system. The MEA photo-conferencing service was deployed in an active conference environment in which real world constraints such as network load, packet loss, user preferences etc directly affected user's experience with and perceptions of the mobile services.

6.6.1 Study Methodology

6.6.1.1 Design

The field-based study involved groups of 2 to 3 participants who were recruited during the special demo reception at the ACM 2008 Conference on Computer Supported Cooperative Work. Each group was in the same vicinity (verbally collocated) and provided with devices to interact and share images using the MEA photo-conferencing service. Data collection was performed through direct observation and activity (server based pass through) logs. These were conducted at a group and individual participant level.

6.6.1.2 Interaction Techniques

Participants were provided with the four previously reported interaction techniques, pointing, scaling, mixed and hybrid conditions, and with a further two interactions: the ability to capture and share new or existing images on the device and the ability to switch between shared images (see Figure 5.15, 5.10 and 5.11). All interactions were designed to be controlled independently on each device (i.e. synchronously by any participant across all devices) using dedicated hardware buttons on the mobile keypad. The keypad layout was modified (see Figure 6.32) to accommodate the additional interactions, using a combination of ten buttons comprising: the hash key, directional pad (up, down, left, right, enter, back) and the number keys 1, 2 and 3.

The hash key was used to toggle between the different interaction modes.

- Pointing: Indicated by the presence of a pointer on the screen.
- Hybrid: Indicated by the presence of a grid layout on the screen.
- Scaling: Indicated by no on-screen elements.
- Mixed: The use of the toggle key enables the mixed condition by allowing users to toggle freely between the Pointing and Scaling interaction techniques.

The directional-pad (up, down, left, right, enter, back) was contextual, based on the type of input mode selected:

- Pointing: The direction pad moves the pointer so that it can be positioned anywhere on the screen. The enter-key shrinks the pointer's selection area and the back-key enlarges the selection area.
- Scaling: The direction pad moves the active image so that it can be positioned anywhere on the screen. The enter-key scales into the viewable area and the back-key scales out of the viewable area.
- Hybrid: The direction pad allows for co-ordinate selection. The enter-key scales into the active co-ordinate area and the back-key scales out of the selected co-ordinate area.

Figure 6.32: User interface input controls.

Figure 6.33. Image selection (top), capture (middle) and collaborative distribution (bottom).

Participants were also able to switch between images in the shared session using the keys 1 and 3. The first navigates the user to the previous image in the thumbnail list and the latter navigates to the next image in the thumbnail list (see Figure 6.33 Bottom and 5.11).

Also, multiple images could be added to the shared session (depicted by a thumbnail list) through the use of the number 2-key. After which users are presented with a list of all images (see Figure 6.32 top) and an option to select either an existing image from the user's device or to use the built-in camera to capture a new image for sharing (see Figure 6.32 Middle and Bottom).

Similarly to the lab based studies, the animation speed at which all actions occur on user input was set to 500 milliseconds from start to finish due to processor limitations, and any event occurring on one device's screen made the same event occur synchronously on the other device's screen.

6.6.1.3 Procedure

The study consisted of observations of participants interacting using the MEA photo-conferencing service, followed by a questionnaire. Throughout the study, there were three main categories for data collection: (1) An evaluation of the initial user experience; (2) Engagement with the MEA Photo-conferencing service; (3) Participants' reactions to the MEA service, particularly feedback and future directions.

The system was presented to users as an early showcase of the use of everyday mobile devices as viable alternatives to fixed desktop based cooperative solutions when users are on the go. This allowed us to frame a much broader picture for the technology and gain additional feedback. For the field observations the following structure was used:

- Two to three participants were provided with the MEA mobile handset.
- An interactive media exchange session was automatically initiated.
- Participants were provided with a brief demonstration of the technology and an overview of the input keys used during the interactions.
- Participants were allowed to engage freely with one another using the MEA photo-conferencing and its remote gestural interaction mechanisms.

During the interaction each group was shadowed and observed, after which each participant was individually interviewed, normally following their shared engagement. In the interviews we discussed participants' use of the MEA photo-conferencing service and some of the more interesting observations from the shadowing. Finally, each participant was asked to complete a quick survey to gauge their mobile phone use, experience and feedback regarding the photo-conferencing service.

6.6.1.4 Participants

We ran 21 participants who took part in groups of 2 to 3 users at a time. The field-based observations involved inviting groups of participants to take part in a photo-conferencing session. Participants were randomly recruited from those attending the Computer Supported Cooperative Work conference and, despite an attempt in random selection, the majority of groups comprised users that previously knew each other. This offered the advantage of allowing the participants to be at ease during their interactions, with many offering each other assistance during the photo-conferencing session.

All the participants volunteered to be observed during their interactions and take part in a small questionnaire to gauge their previous phone use and feedback. Four participants were female and post-study questionnaires indicate that all participants were well versed in the use of mobile telephony devices, with the majority rating over five years of mobile phone usage.

6.6.1.5 Apparatus

Similar to the previous lab based studies, smartphone (non-touch screen) mobile devices were used throughout the experiments enabling one or two handed input using the directional keypad and the built-in T9 input keys. Also each mobile device was pre-loaded with a custom built stand-alone Windows Mobile Photo-Conferencing client (see Chapter 5), that established communication between the two mobile devices, creating a shared visual space in which a number of communication conditions could be utilised.

Differing from the lab based studies, the Photo-Conferencing client allowed users to explore the full range of communication capabilities, including all four remote interaction techniques “Pointing”, “Scaling”, “Mixed” and “Hybrid” and the facility to capture new photos and instantly share them with group members in addition to sharing any existing photos on the device itself and the ability to switch between shared images.

The six devices used in the experiment were all windows mobile based with similar specifications, the application was always run in full screen mode and the devices were fully charged where possible to reduce any processor throttling effect on transmission speeds.

In addition to providing each user with a hands-on demonstration of the technology, a laptop was set-up to provide a brief pre-recorded video presentation that could be displayed repeatedly to passersby. The video was itself concise (less than two minutes in length) and covered an introduction to the MEA photo-conferencing service and a demonstration of the system and devices.

6.6.1.6 Problems Encountered

No major problems were encountered with the hardware or software, although very high network latency and bandwidth fluctuations were frequently observed. This was primarily due to the conference environment and the limited bandwidth available at the venue in which the conference took place. However, despite the network latency the MEA was still able to facilitate communication between the participants and was able to distribute the image successfully albeit at a slower rate.

6.6.2 Analysis

Several types of quantitative and qualitative data were gathered. Server side pass-through logging was instrumented to log time-stamped records of all interactions, including events related to the type of interaction method used and the number of photos shared. All groups were observed by the experimenter and notes were taken throughout. Finally, after using the system all participants completed a questionnaire containing both Likert-scale [Williges 1996] and free-form questions. The questionnaire incorporated a 5-point Likert scale, and the participants selected a response to each statement that ranged from ‘strongly agree’ to ‘strongly disagree’.

6.6.2.1 Timing Analysis

Analysis of the server logs provided insight into the interaction techniques used most by the participants (see Figure 6.34). We categorised interactions according to six distinct groups, based on the facilities provided by the MEA Photo-conferencing system:

- Sx01: In combination with participant observations this defines the percentage time users spent looking or talking about an image or photo being shared during a shared session. This can more specifically be defined as the amount of time when no interface interaction took place, i.e. no other interaction such as pointing, scaling or switching etc were being performed.

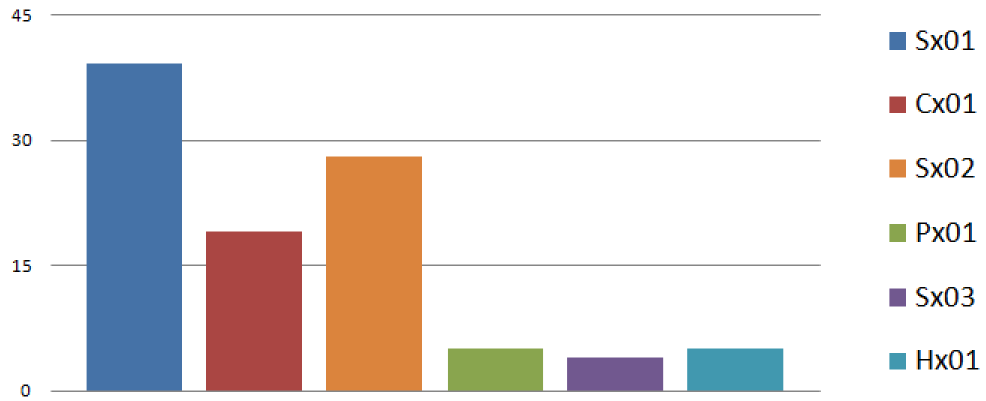

Figure 6.34. Photo-conferencing functionality categorised by participant use during a collaborative session, displayed as percentage.

- Cx01: Defines the amount of time users were engaged in the process of adding new images to the shared session. This includes images captured through the camera or from the phone's built in memory card.

- Sx02: Defines the amount of time users were engaged in the process of switching between the different images captured during the shared session. This includes the time spent navigating back and forth between the different images added to the shared session.

- Px01: Defines the amount of time users were engaged in the pointing interaction condition. This includes time related to positioning the pointer on the screen, in addition to shrinking and enlarging the pointer selection area.

- Sx03: Defines the amount of time users were engaged in the scaling interaction condition. This includes time related to positioning the image on the screen, in addition to scaling into and out of the viewable image area.

- Hx01: Defines the amount of time users were engaged in the hybrid interaction condition. This includes time related to co-ordinate selection, in addition to scaling into and out of an active co-ordinate area.

Findings in relation to observations indicate that the main portion of time spent during a shared session (39%) was dedicated to viewing and conversing over the images being shared. This was followed by the act of navigating between the different images being shared (28%), the act of sharing new images (19%), performing hybrid interactions (5%), performing pointing interactions (5%) and finally performing scaling interactions (4%).

These results demonstrate the differences between lab-based studies and that of a typical mobile cooperative session. In our previous lab based studies we observed that the gestural interactions accounted for the dominant portion of time throughout the shared session (see Table 6.1). This was due to the nature of the task involved, i.e. the puzzle based task in which participants were provided with an elevated situation that wouldn't typically occur except under the most demanding mobile cooperative scenarios and were asked to perform the task in as little time as possible.

The field study results are reassuring and highlight the nature of media exchange, in which, as observed, the content of the shared interaction space plays a key role in the shared communication session and, although very useful, the remote gestural interaction techniques are secondary.

6.6.2.2 Conversation Analysis

Field-based observations and note taking were used to gather information on the verbal queues employed by participants. These observations identified a number of general strategies users adopted to support their shared interactions, verbal framing being the most common. When users exchanged photos they often took advantage of the limited screen size to frame the image and refer to the elements using the screen itself as a co-ordinate system, e.g. "look at the top right of your screen".

Figure 6.35. Screen size and referential awareness.

These results are similar to earlier findings in which positioning elements in the shared workspace allowed users to better convey deictic referencing (see 6.4.2.3). They also suggest that the limited screen size afforded by most common cellular devices may actually benefit deictic referencing across mobile devices. Images on mobile cellular devices occupy the largest proportion of the available screen space including the edges of the screen. This allows the borders of the mobile screen to form natural identifiers for referential awareness between users which would not typically be the case on desktop computers in which image content may only occupy a small portion of the screen (see figure 6.35).

Although it would have also been beneficial to gather data on the use of verbal queues in correspondence with the exact inputs being conducted on the mobile keypad to better assess 'photo talk' [Frohlich, et al. 2002], environmental noise and limitations in the logging mechanisms available to us in the field setting prevented the accurate collection of such data.

6.6.2.3 Event Analysis

Similar to previous work, the event-logs recorded during the observations provided data on the number of key-presses utilised during each observation (see Figure 6.36). The data was collected using the photo-conferencing service's built-in event logger which was active throughout all sessions. The results of the event log can be seen in Table 6.9 (first row).

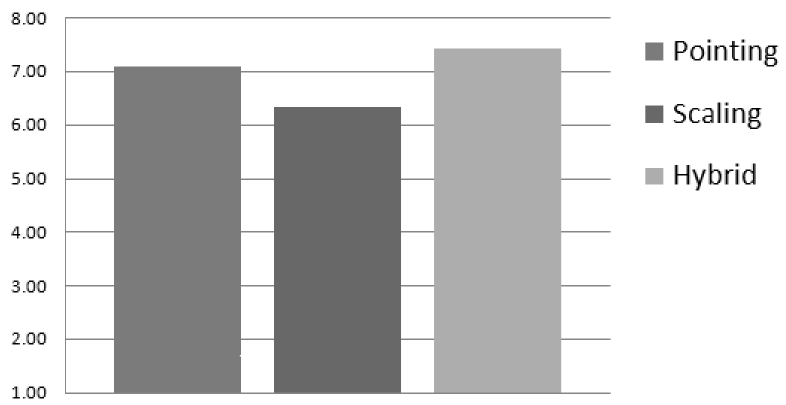

Figure 6.36. Mean number of key presses across conditions.

The participants in the field-based observations were not restricted to a single interaction method. Results (see Table 6.11) and observations indicated that participants didn't adopt a specific remote interaction technique during the shared sessions but used the available techniques interchangeably. A one-way ANOVA across the three conditions found no significant effect on the number of key-presses used during the task ($f_{2,33}$ = 7.38, n.s.). The results also suggested no significant preference for a particular interaction method, with pointing accounting for 34% participant usage, scaling 30.4% participant usage and Hybrid 35.6% participant usage.

Observations also highlighted two distinct classes of users. Those that adopted an exploratory approach in which each interaction was used in turn, before settling on a preferred method and those that only used the first interaction method they came across and adapted their interactions accordingly. Although the majority of the participants were well versed in the use of mobile devices, these results highlight the need to design systems to cater to varying usage scenarios [Cooper and Reimann 2004].

Table 6.9: Mean (and SDs in parentheses) performance of collaborating pairs across conditions (Events: number of key presses).

	Pointing	Scaling	Hybrid
Events	7.08 (3.09)	6.33 (2.50)	7.42 (2.15)

6.6.2.4 Subjective Feedback

User satisfaction is often used as an aggregate of the subjective measure [Olaniran 1995]. A five-point Likert scale was used to measure satisfaction; the characteristics of this scale include a statement with a five-point rating scale, a horizontal and continuous scale with five labelled anchors, and equivalent intervals between anchors. The anchors were "strongly agree" (weight equal to five), "agree" (weight equal to four), "neither agree nor disagree" (weight equal to three), "disagree" (weight equal to two), and "strongly disagree" (weight equal to one).

After using the photo-conferencing service we asked participants a number of questions to gauge feedback and satisfaction levels. The results for the post-study questionnaire based on the five-point Likert scale can be seen in Table 6.10. The overall results were very positive. Participants found collaboration using the Photo-conferencing system easy (mean = 4.09; SD = 0.76); that the interaction methods didn't hinder collaboration (mean = 3.80; SD = 0.81); and they found the interaction methods useful (mean = 4.14; SD = 0.57).

Table 6.10: The mean responses to the Likert-scale questions completed by each of the participants from 1 = strongly disagree to 5 = strongly agree.

	Mean
I found it easy to collaborate this way	4.09
I was not constrained by the interaction method	3.80
I enjoyed using collaborative service	4.61
I found the interaction methods useful	4.14
I felt satisfied with the facilities available for sharing images	4.38

In terms of the overall use of the Photo-conferencing service, participants were positive about the facilities provided by the system, e.g. image sharing, capturing, switching and gestural interactions (mean = 4.38; SD = 0.66) and, just as importantly, they highly enjoyed using the collaborative service (mean = 4.61; SD = 0.49).

The participants were able to quickly learn and then successfully perform each of the remote interaction techniques. In general, participants seemed able to quickly learn to use the Photo-conferencing service and switch between its interactions without any noticeable trouble.

Overall reactions to the MEA Photo-conferencing service were very positive with many keen to try out the technology. Furthermore, after the questionnaire many of the participants stayed behind to discuss several possible additions to the system and also suggested several new directions for future research. These have been summarised at the end of the chapter.

6.7 Chapter Summary

In the scaling condition, which showed the second best performance overall, participants tended to use relative referencing (of surrounding items). In contrast, users of pointing (with an area box) tended to use precision referencing. Relative referencing dominated in the hybrid condition, which showed the best performance. Thus, the type of interaction techniques offered to mobile users can have a strong impact on their communication strategy and in the case of the hybrid interaction technique can essentially direct users into employing an optimal communication scheme.

The interaction techniques' support for relative and precision referencing, rather than the specific interaction mechanisms *per se*, may underlie the differences in the results. Users of pointing tended to use precision referencing. In contrast, in the scaling only condition, which showed the second best performance overall, participants tended to use relative referencing. Relative referencing again dominated in the hybrid condition, which showed the best performance overall. Thus, users' preferential use of pointing when given a straight choice between pointing and scaling (in the mixed condition) may have led them to use a less effective form of referencing.

The Hybrid results show a reduction in task completion time compared to previous relative referencing (scaling only condition), precision referencing (pointing only condition) and the simple offering of both relative and precision referencing (mixed condition) findings. Results further indicate that the hybrid approach led to a significant reduction in task completion time, number of words required and the number of events needed to complete the shared task, minimising collaborative effort [Clark and Brennan 1991]. Durkheim [1938] wrote that "whenever certain elements combine and thereby produce, by the fact of their combination, new phenomena, it is plain that these new phenomena reside not in the original elements but in the totality formed by their union". In our "hybrid" interaction technique, the synthesis of the best relative and precision referencing characteristics produced a new interaction that enhanced our overall results and supported H2:

> *[H2] An enhancement to the relative referencing interaction provided by the scaling mechanism and the integration of a complementary precision referencing facility (rather than simple juxtaposition of pointing and scaling techniques) would further improve the mobile collaborative performance measurements (task completion time, number of words used by the participants, number of key-presses, error rates and measure of cognitive workload), minimising collaborative effort [Clark and Wilkes-Gibbs 1986].*

Findings from our field-based observations identified several enhancements that could be made to the MEA photo-conferencing system:

- Expanded annotation and drawing support to further enhance the playfulness of the interaction, e.g. for drawing moustaches, glasses, horns etc.

- A text based conversation channel: this was suggested as being useful for scenarios in which verbal communication could not take place, e.g. in quiet zones such as libraries or during conference talks.

- Photo Ringtones: in which for example a photo "captured during a night out" could be pushed to a recipient device to be displayed during the ringing process, making for an interesting conversation starter.

In addition the field-based observations identified several directions for future mobile collaborative research, including:

- Collaborative editing: Allowing multiple fixed and mobile users to edit and work with shared resources including documents, files and media. Variations on this theme include version control and track editing features.

- Network Play: Given the existing demand for basic gaming with mobile devices, it is not difficult to see why the advent of interactive mobile collaborative gaming sessions between players from around the world was a popular talking point and suggestion.

- Social Communication: The popularity of social networks raises the question of possible integration strategies with existing social networking services such as Facebook, Flickr and MySpace to provide real time status and activity notifications.

Throughout the studies reported in this chapter, we observed an enthusiasm and high level of demand for the technology. Many of the ideas for future research came directly from user suggestions and are highlighted in the next chapter as targets for further exploration.

Chapter 7.

Summary & Future Work

“. . . the moment man first picked up a stone or a branch to use as a tool, he altered irrevocably the balance between him and his environment. From this point on, the way in which the world around him changed was different. It was no longer regular or predictable. New objects appeared that were not recognizable as a mutation of something that had existed before, and as each one emerged it altered the environment not for a season but forever. While the number of these tools remained small, their effect took a long time to spread and to cause change. But as they increased, so did their effects: the more the tools, the faster the rate of change” James Burke, *Connections*

7.1 Summary

In this research we have extended the state of the art in mobile cellular interactions and vastly expanded the richness afforded to remote mobile users beyond those capabilities presented to date in the commercial and research fields. We have progressively transitioned from a review of the literature, to the creation of a comprehensive functioning mobile digital media exchange system, through the design and development of an exemplar application and its evaluation and subsequent enhancements to develop improved remote mobile interaction techniques.

Our research presents a fully functional MEA supporting shared remote interaction techniques and simultaneous voice communication across cellular devices. The MEA supports services such as a mobile photo-conferencing service in which real time interactive media sharing can occur between mobile users during an active phone call. This instantiation enables mobile cellular users to talk, exchange and manipulate photos synchronously in a single application. It works effectively across a diverse range of mobile devices with highly constrained displays, keypads and processing power.

The system based on an architecture led investigation into mobile media sharing supports two working modes, synchronous and asynchronous: one in which real time interactions are shared with all participants and the other in which users can join, leave and catch up later at any time. Scalability was a core part of the architectural design. The system currently supports multiple users and separate sessions (see Figure 7.1), enabling simple one-to-one shared sessions through to large-sessions comprising many connected users, all sharing and participating in shared spaces across their mobile cellular devices. A robust distributed co-ordination engine is responsible for the management of all active cooperative sessions and supports scenarios from simple media- and location-sharing services to distributed gaming utilising an extensible plug-in systems architecture.

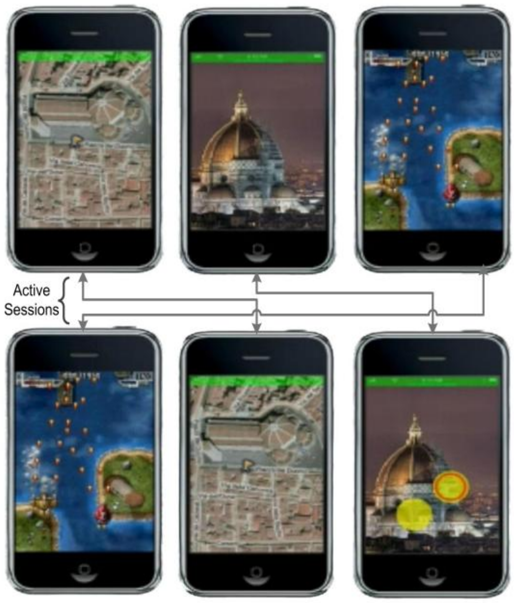

Figure 7.1: Support for multiple concurrent mobile cooperative sessions across cellular networks.

We have reported experimental evaluations and a field study investigating different interaction techniques designed to support communication across highly resource constrained mobile devices. Specifically, we investigated the effects of these interaction techniques on the collaborative effort required by users, their actual and perceived performance. We have demonstrated that rich mobile communication can be achieved through the use of effective remote interaction techniques [Yousef and O'Neill 2008]. Our refinements of these techniques have provided improvements to both user perceived and actual performance metrics.

7.2 Further Work

We consciously ran our studies on standard mobile phones with built-in keypads, relatively small displays and less powerful processors due to their popularity and massive worldwide sale volumes. This research could have taken the simpler route of using laptop computers, which are also commonly referred to as "mobile" devices. However, laptops are often bulky and battery-hungry, making them suitable only for "pause workers" who can grab 10 minutes at a table somewhere.

Further research could extend our mobile phone findings and investigate the use of alternative mobile interface techniques that are beginning to become popular, such as touchscreens. Issues include designing and evaluating potentially different interaction mechanisms for alternative physical interfaces, investigating the relationships between relative and precision referencing and the specific features of different mobile interaction techniques, and investigating how multiple devices with an even greater diversity of form factors and interaction techniques can support users interacting in the same session.

Architecture load tests of fifty simultaneous users were performed on the photo-conferencing instantiation and although the results indicated that a greater number of simultaneous sessions could have been supported on the mid-range server hardware used. Further research into the scalability of such mobile infrastructures and the use of more finely tuned load balancing techniques could better facilitate such mobile services in supporting a greater number of simultaneous users across separate and shared sessions.

From our user studies, on average the lowest recorded task completion time was 45 seconds (for the scaling condition), compared to the highest recorded 4 minutes (for the mixed condition). Added to the initial training time, the average hands-on use of the photo-conferencing system by the first time participants was less than 15 minutes. It would, of course, be very interesting to run further studies based on extended use, particularly in more natural settings and with a range of photos and other visual content that users chose to share.

Future designs could incorporate mechanisms for conflict resolution between connected peers, e.g. using accelerometers to detect users shaking their screens to enforce floor control. Although haptic feedback was implemented through the phones' built in vibration mechanisms, we could not effectively evaluate its use due to the technical limitations of the devices used in our studies. The phones, in common with similar devices, had difficulty performing additional I/O (input output) operations such as vibration during periods of dedicated CPU utilisation, e.g. image manipulation (scaling, pointing) or heavy networking activities. The advent of mobile GPUs (Graphical Processing Units), higher processing speeds and multiple cores in upcoming devices will overcome many of these limitations and allow for greater interactional richness during mobile media exchange sessions.

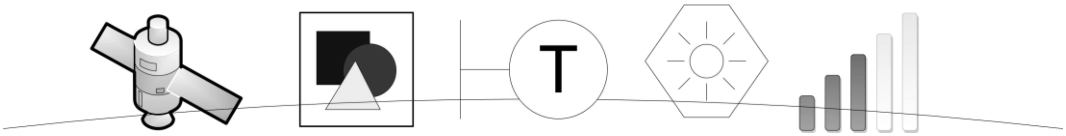

Figure 7.2: Access to mobile sensory data, location information and environmental readings will define future MEAs.

As cell phone technologies continue their rapid evolution, mobiles may come to resemble mini-computers more than pocket telephones. The rate at which this technology appears to be developing is astounding, as today's high-end mobiles are fast becoming tomorrow's obsolete bricks. Present day Britain houses around 50 million mobile phone users, compared with 25 million in 2000. This figure looks set to carry on rising as mobile phone companies continue to make phones and phone contracts increasingly affordable.

The rapid evolution of processing functionality combined with the latest sensory capabilities that are included with the latest cellular handsets will greatly benefit future mobile collaboration architectures (see Figure 7.2). We are going to see more sensors such as GPS and environmental monitoring data being readily available for sharing in shared sessions among users.

Mobile exchange architectures will enable new opportunities such as real-time context sharing among users; enabling future devices to adapt not only to their users activities but to the activities of their friends as well. With the advent of sensory technologies into the mix, people may no longer have to ask a person they are calling "how's the weather?" but will have ready access to such ambient information directly at their finger tips. Such cooperative mobile architectures, especially involving large groups of users, could lead to interesting research questions on the impact of augmented conversations, storytelling and social interaction across people synchronously connected by their mobile devices.

We predict that mobile collaboration in the future will play many roles in personal communication. As the medium becomes increasingly available in our hands and pockets, people will evolve new ways of using it. Integration with existing fixed computing environments, sensor networks and novel user interactions will present new opportunities to enable a range of innovative scenarios and communication modalities. We believe the research reported in this thesis to be part of the first phase of a new era in scalable always-to-hand mobile collaborative solutions. We must continue the work, exemplified in this thesis, both on building the technical capabilities and on understanding how people can better interact and communicate to realize the full potential of this new medium.

7.3 Conclusion

This thesis has set out to advance the field of mobile-to-mobile communication, by asking a simple question: "*How can we better design systems to support interactive media exchange across resource constrained mobile cellular devices?*"

This resulted in the design, construction and creation of a complete Mobile Exchange Architecture based on requirements derived from the literature, an in depth knowledge of mobile networks, distributed cellular interactions and mobile user-interface development. Additionally a series of lab-based and field-based studies was conducted, in which the utility of mobile media exchange was investigated, both qualitatively examining its cooperative function and quantitatively exploring its impact on facets of task performance. The system evaluation was designed as a feedback loop in which new knowledge and requirements could be used to enhance mobile media exchange and further its capabilities to exchange rich media across mobile devices. To draw this thesis to a close, the key contributions of the research will be summarised.

1. Advances the field of mobile communication and presents an architecture lead investigation in to the design and development of mobile exchange architectures (MEAs) in which local and remote mobile users can share, synchronously interact and converse during an active phone conversation.

2. Presents a new complete mobile exchange architecture, client software and adaptation techniques that enable users to establish mobile-to-mobile sessions, exchanging large amounts of data and maintaining a shared visual space amongst collocated and remote cellular devices.

3. Presents an iterative experimental evaluation of mobile gestural interaction techniques, Scaling, Pointing, Mixed and Hybrid for mobile-to-mobile media exchange, assessing their impact on collaborative effort [Clark and Brennan 1991].

7.4 Closing Remarks

If we look back at the rapid evolution of mobile cellular networks and devices, the number of services that have defined the way in which we communicate today can be counted on a single hand: Voice, Text Messaging, Multi Media Messaging and more recently the Internet. Amongst these, voice still remains to date the only synchronous service between mobile devices. In this thesis we have demonstrated that not only are richer solutions possible over existing 3G networks, but that they can both augment existing services such as voice and enable the next generation of mobile communication capabilities and connectedness.

While further work remains in order to comprehensively explore the field of Mobile Exchange Architectures (MEAs) and the interaction techniques they will present, this thesis provides a step forward as well as a direction for the future development of complementary technologies to better enable mobile collaboration. As these mobile technologies and capabilities evolve, so too will user needs and what they will come to expect from their mobile devices. To date the field of Mobile Collaboration remains in its infancy. As research progresses the future will present greater opportunities that will delight, inspire and challenge our notions of what is achievable on the once very limited devices that we carry in our hands, pockets and bags as we journey onwards to new destinations.

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Appendix A.

Companion to Chapter 2

Appendix A.1: HTC-S710 Device Specifications

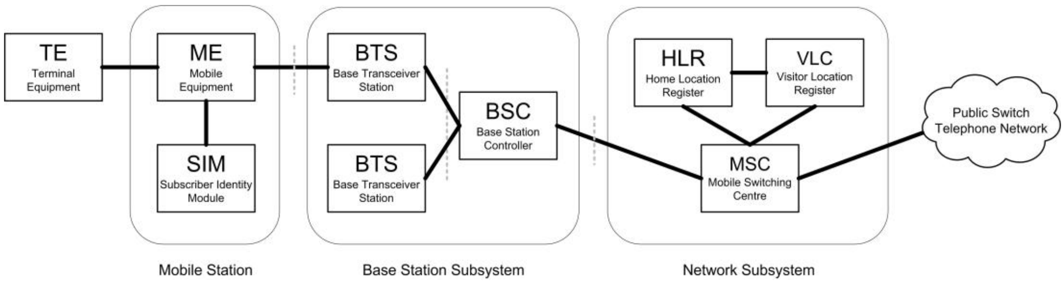
Release Date:	April, 2007
Software Environment	
Operating System:	Windows Mobile 6 Standard
Microprocessor	
CPU:	32bit Texas Instruments OMAP 850
CPU Clock:	201 MHz
Memory, Storage capacity	
ROM capacity:	128 MB (accessible: 63.4MB)
RAM capacity:	64 MB (accessible: 49.6MB)
Display	
Display Type:	color transflective TFT , 65536 scales
Display Resolution:	240 x 320
Display Diagonal:	2.4 "

Cellular Phone	
Cellular Networks:	GSM850, GSM900, GSM1800, GSM1900
Cellular Data Link:	CSD, GPRS, EDGE
Call Alert:	64 -chord melody
Vibrating Alert:	Supported
Control Peripherals	
Primary Keyboard:	Slide-out QWERTY-type keyboard, 37 keys
Secondary Keyboard:	Built-in numeric phone keyboard, 18 keys
Directional Pad:	5 -way block
Interfaces	
Expansion Slots:	microSD, microSDHC, TransFlash, SDIO
Serial:	RS-232 , 115200bit/s
USB:	USB 2.0 client, 480Mbit/s , USB Series Mini-B (mini-USB) connector
Bluetooth:	Bluetooth 2.0
Wireless LAN:	802.11b, 802.11g
Built-in Digital Camera	
Main Camera:	CMOS sensor, 1.9MP
Built-in Flash:	Not supported
Power Supply	
Battery:	Lithium-ion , removable
Battery Capacity:	1050 mAh

Appendix B.

Companion to Chapter 3

Appendix B.1: GSM Architecture



- Mobile Station (MS): The MS is a combination of terminal equipment and subscriber data. The terminal equipment is called ME (Mobile Equipment) and the subscriber's data is stored in a separate module called SIM (Subscriber Identity Module). A mobile station can be a basic mobile handset or a more complex Personal Digital Assistant (PDA). When the user is moving (i.e. while driving), network control of MS connections is switched over from cell site to cell site to support MS mobility through a process called handover.

- Base Transceiver Station (BTS): The BTS implements the air communications interface with all active MSs located under its coverage area (cell site). This includes signal modulation/demodulation, signal equalizing and error coding. Several BTSs are connected to a single Base Station Controller (BSC). In the United Kingdom, the number of GSM BTSs is estimated at around several thousand. Cell radii range from 10 to 200 m for the smallest cells to several kilometres for the largest cells. A BTS is typically capable of handling 20–40 simultaneous communications.

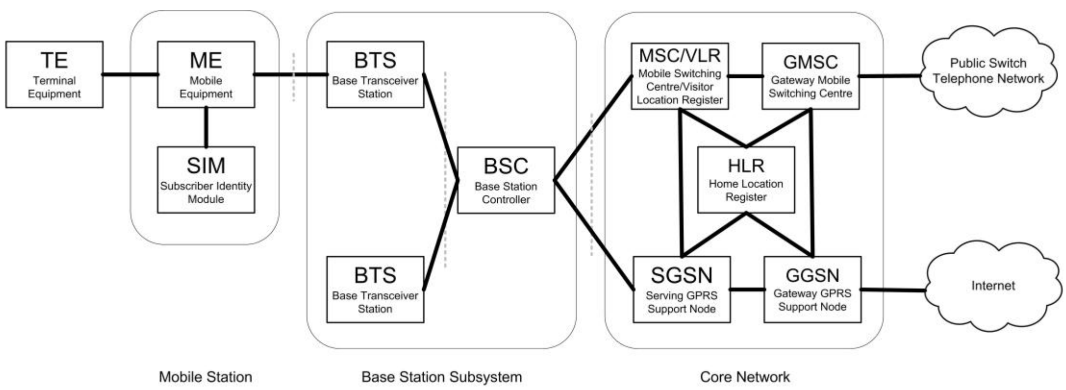
- Base Station Controller (BSC): The BSC supplies a set of functions for managing connections of BTSs under its control. Functions enable operations such as handover, cell site configuration, management of radio resources and tuning of BTS radio frequency power levels. In addition, the BSC realises a first concentration of circuits towards the MSC. In a typical GSM network, the BSC controls over 70 BTSs.

- Mobile Switching Centre (MSC): The MSC performs the communications switching functions of the system and is responsible for call set-up, release and routing. It also provides functions for service billing and for interfacing other networks.

- The Visitor Location Register (VLR): The VLR contains dynamic information about users who are attached to the mobile network including the user's geographical location. The VLR is usually integrated to the MSC. Through the MSC, the mobile network communicates with other networks such as the Public Switched Telephone Network (PSTN), Integrated Services Digital Network (ISDN), Circuit Switched Public Data Network (CSPDN) and Packet Switched Public Data Network (PSPDN).

- Home Location Register (HLR): The HLR is a network element containing subscription details for each subscriber. A HLR is typically capable of managing information for hundreds of thousands of subscribers.

Appendix B.2: Second Generation GSM Architecture



- Mobile Station (MS): The MS is a combination of terminal equipment and subscriber data and is similar to that of the earlier GSM systems. However, updates to the MS to support data connectivity have resulted in three different operating modes [3GPP-22.060] to the BTS:

Class A: The mobile station supports simultaneous use of GSM and GPRS services (e.g. attachment, activation, monitoring, and transmission) and may establish or receive calls on the two services simultaneously. There are very few mobiles supporting this class on the market as these devices requires lots of CPU bandwidth which would make them more expensive.

Class B: The mobile station is attached to both GSM and GPRS services. However, the mobile station can only operate in one of the two services at a time.

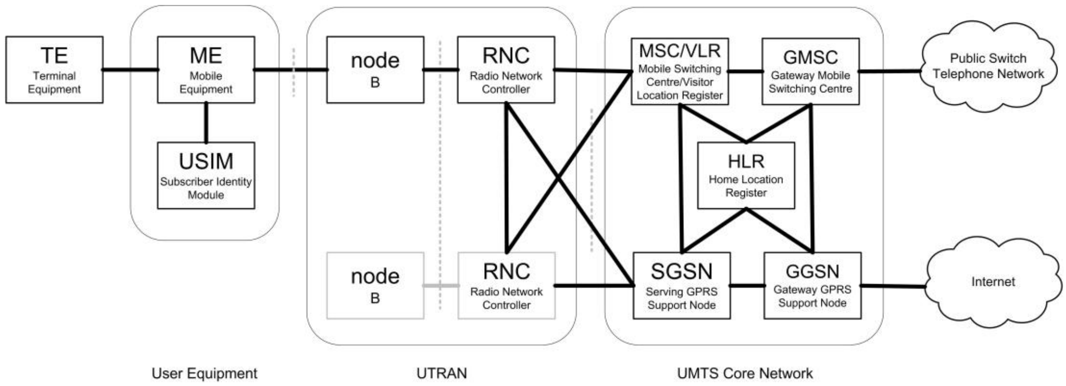
Once the voice call has terminated, the data service can be resumed. Most phones on the market are currently of this class.

Class C: The mobile station is attached to either the GSM service or the GPRS service but is not attached to both services at the same time. Prior to establishing or receiving a call on one of the two services, the mobile station has to be explicitly attached to the desired service. This class is generally used by GPRS modems which are not used for voice calls.

- Serving GPRS Support Node (SGSN): The SGSN is connected to one or more base station subsystems. It operates as a router for data packets for all mobile stations present in a given geographical area. It also keeps track of the location of mobile stations and performs security functions and access control.

- Gateway GPRS Support Node (GGSN): The GGSN ensures interactions between the GPRS core network and external packet-switched networks such as the Internet. For this purpose, it encapsulates data packets received from external networks and routes them toward the SGSN.

Appendix B.3: Third Generation GSM Architecture



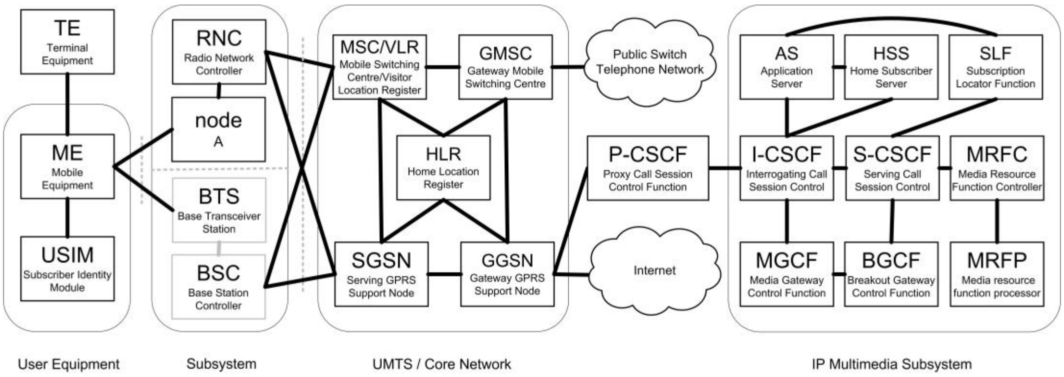
- User Equipment (UE): The UE is the same as the Mobile Station (MS), usually provided to the subscriber in the form of a handset composed of Mobile Equipment (ME) and a UMTS Subscriber Identity Module (USIM). The ME contains the radio transceiver, the display and digital signal processors. The USIM is a 3G application on an UMTS IC card (UICC) which holds the subscriber identity, authentication algorithms and other subscriber-related information.

- UTRAN Network: The UTRAN is composed of nodes B and Radio Network Controllers (RNCs). The node B is responsible for the transmission of information in one or more cells, to and from UEs. It also participates partly in the system resource management. The node B interconnects with the RNC via the Iub interface. The RNC controls resources in the system and interfaces the core network.

- UMTS Core Network: The first phase UMTS core network is based on an evolved GSM network sub-system (circuit-switched domain) and a GPRS core network (packet-switched domain). Consequently, the UMTS core network is composed of the HLR, the MSC/VLR and the GMSC (to manage circuit-switched connections) and the SGSN and GGSN (to manage packet-based connections).

- Second Phase UMTS: The initial UMTS architecture presented in this chapter is based on evolved GSM and GPRS core networks (providing support for circuit-switched and packet-switched domains, respectively). The objective of this initial architecture is to allow mobile network operators to rapidly roll out UMTS networks on the basis of existing GSM and GPRS networks.

Appendix B.4: IMS (IP Multimedia Subsystem) Architecture.



- Proxy Call Session Control Function (P-CSCF): The P-CSCF is a SIP proxy that is the first point of contact for the IMS terminal. It can be located either in the visited network (in full IMS networks) or in the home network (when the visited network isn't IMS compliant yet). The terminal discovers its P-CSCF with either DHCP, or it is assigned in the PDP Context in General Packet Radio Service (GPRS).

  The P-CSCF authenticates the user, establishes an internet protocol security association with the IMS terminal, preventing spoofing attacks and replay attacks, and protects the privacy of the user. Other nodes trust the P-CSCF, and do not have to authenticate the user again.

- Interrogating Call Session Control (I-CSCF): The I-CSCF is another SIP function located at the edge of an administrative domain. Its IP address is published in the Domain Name System (DNS) of the domain (using NAPTR and SRV type of DNS records), so that remote servers can find it, and use it as a forwarding point (e.g. registering) for SIP packets to this domain. The I-CSCF queries the HSS using the Diameter Cx interface to retrieve the user location (Dx interface is used from I-CSCF to SLF to locate the needed HSS only), and then routes the SIP request to its assigned S-CSCF.

- Serving Call Session Control (S-CSCF): The S-CSCF is the central node of the signalling plane. It is a SIP server, but performs session control too. It is always located in the home network. It uses Diameter Cx and Dx interfaces to the HSS to download and upload user profiles and has no local storage of the user. All necessary information is loaded from the HSS.

- Application Server (AS): AS host and execute services, and interface with the S-CSCF using Session Initiation Protocol (SIP). An example of an application server that is being developed in 3GPP is the Voice call continuity Function (VCC Server). Depending on the actual service, the AS can operate in SIP proxy mode, SIP UA (user agent) mode or SIP B2BUA (back-to-back user agent) mode. An AS can be located in the home network or in an external third-party network.

- Subscription Locator Function (SLF): The purpose of the SLF function is to locate the HSS and S-CSCF assigned to a particular subscriber. This is an indexing function, mapping the user identity to the S-CSCF/HSS according to registration. When the P-CSCF needs to route a request for a subscriber session to the appropriate S-CSCF, the P-CSCF would access this function to determine which S-CSCF has been assigned to the subscriber. Other devices may need to access this function as well, such as an application server supporting services to the subscriber.

- Home Subscriber Server (HSS): The HSS is similar in function to the GSM Home Location Register (HLR) and Authentication Centre (AUC). The HSS is a master user database that supports the IMS network entities that actually handle calls. It contains the subscription-related information (user profiles), performs authentication and authorization of the user, and can provide information about the user's physical location.

- Breakout Gateway Control Function (BGCF): The BGCF is a SIP server that includes routing functionality based on telephone numbers. It is only used when calling from the IMS to a phone in a circuit switched network, such as the Public Switched Telephone Network (PSTN) or the Public land mobile network (PLMN).

- Media Gateway Control Function (MGCF): The MGCF handles call control protocol conversion between SIP and ISUP and interfaces with the SGW over SCTP. It also controls the resources in a Media Gateway (MGW) across an H.248 interface.

- Media Resource Function Controller (MRFC): The MRFC is a signalling plane node that acts as a SIP User Agent to the S-CSCF, and which controls the MRFP across an H.248 interface.

- Media resource function processor (MRFP): The MRFP is a media plane node that implements all media-related functions. The MRFP delivers IP Audio and Video Media processing features as a shared re-usable resource for the numerous multimedia services hosted by the application servers in the IMS.

Appendix C.

Companion to Chapter 5

Appendix C.1: Participant Survey

Section 2/3

[Select A,B or C]

A

B

C

Why:

Section 3/3

[Post Questionnaire]

Gender: Male

Age: 19-25

Additional Comments:

Appendix D.

Companion to Chapter 6

Appendix D.1: Participant Consent Form

Mobile Collaboration Exercise
Participant Consent Form

A study on Mobile Photo-Conferencing is being conducted by Kharsim Yousef (Kam26@Bath.ac.uk) in the Department of Computer Science at the University of Bath.

You are being asked to take part in this study on Mobile Collaboration. Your participation in the evaluation should take less than 30 minutes. The study will be recorded for analysis purposes only. Your responses will be stored anonymously to protect your privacy. If you wish, we shall send you a copy of any subsequent publications that use any of the data from the study. Potential benefits associated with the study include a greater understanding of and design for mobile conferencing services.

If you agree to participate in this experiment as described, and for any relevant responses to be used in publications anonymously, please indicate your agreement by writing your name, e-mail address, then sign and date below. Thank you for your participation in this research.

Name: ....

E-Mail: ....

Signed: .... Date: ....

Appendix D.2: Participant Information Sheet

Mobile Collaboration Exercise

Participant Information Sheet

You will be working in a pair for this experiment. Prior to starting the experimental trials you will be given the chance to try-out the mobile application so that you understand what it does and how it works. The experiment has two trials, each lasting 15 minutes, after each trial you will be required to fill out some questionnaires.

At the beginning of the experiment you will be randomly assigned to either the 'Helper' or 'Worker' role and will swap that role during the second trial. During the task you will be asked to complete a 'dot to dot' diagram. The 'Helper' is the person who will be provided with the instructions required to complete the diagram and will instruct the Worker on what needs to be done.

Both Worker and Helper are encouraged to freely communicate verbally during the task. The Worker is however not allowed to look at the Helpers instructions or know the final outcome of the diagram.

The task consists of connecting a series of nodes (dots) together; as a minimum each node must at least connect to one other node, but there is no limit on the number of connections to or from a singular node i.e. a node can connect to multiple other nodes or just one (see figure 1).

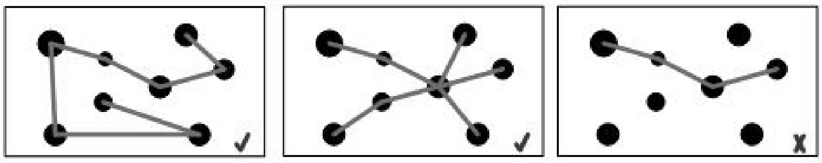


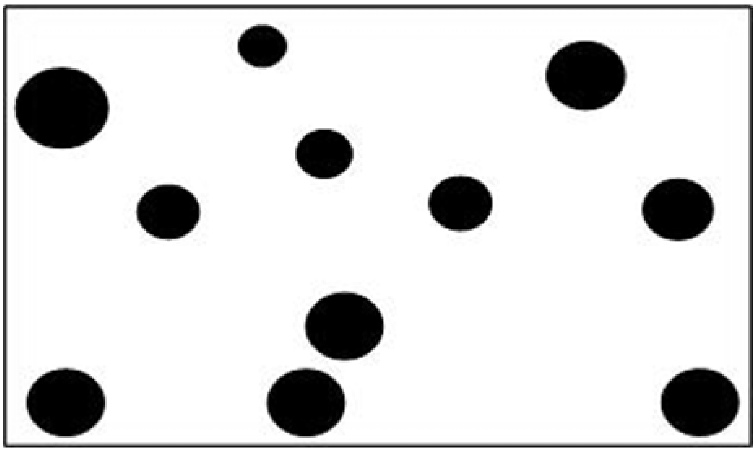
Figure 1: Connection examples, each node must connect to at least one other node.

For each trial the 'Worker' and the 'Helper' sit at separate desks. As mentioned above, in each trial you have 15 minutes, in this time you must complete the task as quickly as possible. After each trial you must complete a mental workload questionnaire (the NASA TLX), and after the second trial you must fill out the third and final part of the mental workload questionnaire and a final evaluation questionnaire as well.

Appendix D.3: Participant Worker Diagram

Mobile Collaboration Exercise
Trial 01 | Participant: 02/**Worker**

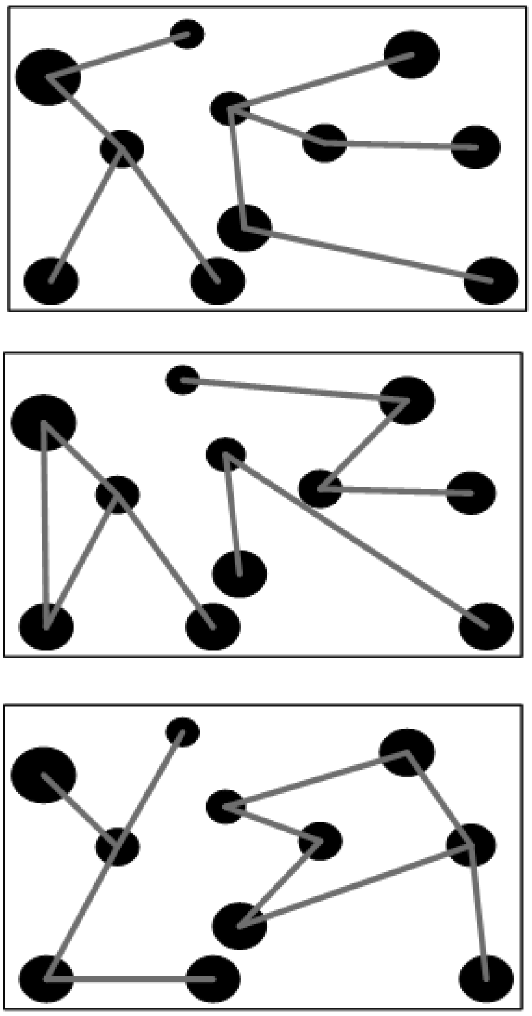
Instructions: Collaborate with the Helper to complete the below diagram.



Appendix D.4: Participant Helper Diagrams.

Mobile Collaboration Exercise
Trial 01 | Participant: 01/**Helper**

Instructions: Collaborate with the Worker to produce the below diagram.



Appendix D.5: Participant post-questionnaire

Mobile Collaboration Exercise

Trial __ | Participant: __/______ | Question Sheet

Instructions: Circle along each scale, to complete the questionnaire.

1) How easy or hard was it to complete the task?

1	2	3	4	5	6	7	8	9	10
Very Hard				Neither					Very Easy

2) How did you find collaborating this way?

1	2	3	4	5	6	7	8	9	10
Very Easy				Neither					Very Difficult

3) How do you feel you did in the task?

1	2	3	4	5	6	7	8	9	10
Very Badly				Neither					Very Well

4) Where you constrained by the interaction method?

1	2	3	4	5	6	7	8	9	10
Strongly Disagree				Neither					Strongly Agree

5) Did you understand what your partner was saying?

1	2	3	4	5	6	7	8	9	10
Yes- always				Half of the time					No- never

5) What problems did you encounter (if any)? (continue overleaf if necessary)

....
....
....
....
....
....

Appendix D.6: Participant post-questionnaire NASA TLX subscales sheet

Mobile Collaboration Exercise

Trial __ | Participant: __/______ | NASA TLX

Instructions: Mark along each scale, the point that best indicates your experience of the task.

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Appendix D.7: Participant post-questionnaire NASA TLX paired-comparisons sheet

Mobile Collaboration Exercise

Trial __ | Participant: __/______ | NASA TLX 2

Instructions: On each of the following 15 questions, CIRCLE the title that represents the more important contributor to the workload for the task.

1)	Mental Demand	**Or**	Physical Demand
2)	Temporal Demand	**Or**	Mental Demand
3)	Temporal Demand	**Or**	Physical Demand
4)	Physical Demand	**Or**	Effort
5)	Performance	**Or**	Physical Demand
6)	Physical Demand	**Or**	Frustration Level
7)	Effort	**Or**	Temporal Demand
8)	Mental Demand	**Or**	Effort
9)	Performance	**Or**	Mental Demand
10)	Mental Demand	**Or**	Frustration Level
11)	Temporal Demand	**Or**	Performance
12)	Frustration Level	**Or**	Temporal Demand
13)	Effort	**Or**	Performance
14)	Frustration Level	**Or**	Effort
15)	Performance	**Or**	Frustration Level

Appendix D.8: Participant Evaluation Questionnaire

Mobile Collaboration Exercise
Participant: __/____ | Post Evaluation Questionnaire

Name: ....

Gender: Male | Female, Age: ....

Are you a student: Yes | No

Major field of study: ...., Year: ....

1) How long have you been using a mobile phone (approx.)?

Years: Months:

2) How many times do you use your phone for calls?

More than 5 per day	2 to 4 per day	Once per day	1-6 per week	1-4 per month	Less than 1 per month

3) How many times do you use your phone for taking photographs?

More than 5 per day	2 to 4 per day	Once per day	1-6 per week	1-4 per month	Less than 1 per month

4) How many times do you use your phone for SMS (text messaging)?

More than 5 per day	2 to 4 per day	Once per day	1-6 per week	1-4 per month	Less than 1 per month

5) How many times do you use your phone for MMS (picture messaging)?

More than 5 per day	2 to 4 per day	Once per day	1-6 per week	1-4 per month	Less than 1 per month

Appendix D.9: Participant Evaluation Questionnaire

6) Do you think this approach made picture sharing easier?

- If yes (why):… ……………………………………………………………………………
……………………………………………………………………………………………
- If no (why):… ……………………………………………………………………………
……………………………………………………………………………………………

7) What feature if added would enhance the collaborative performance?

……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………

8) If you could design the system differently, what would you suggest?

……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………

9) In what scenario would you find it useful over MMS:

……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………
……………………………………………………………………………………………

10) Any other comments:

……………………………………………………………………………………………
……………………………………………………………………………………………
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……………………………………………………………………………………………
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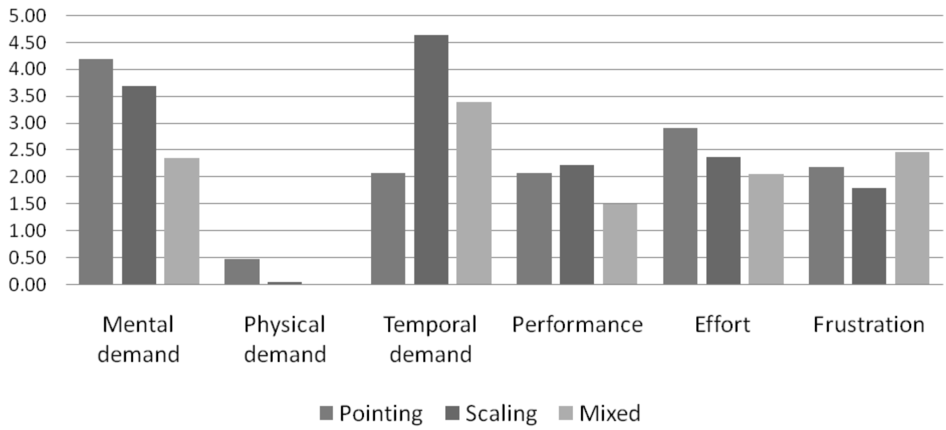
Appendix D.10: Mobile collaboration: Workload Analysis

Table D.10: Mean (and SDs in parentheses) un-weighted mental workload sub-scales by interaction condition: Pointing, Scaling and Mixed.

	Pointing	Scaling	Mixed
Mental demand	16.67 (4.56)	14.25 (7.84)	10.92 (6.08)
Physical demand	6.58 (3.12)	5.08 (2.31)	4.83 (4.78)
Temporal demand	14.25 (8.14)	23.00 (2.98)	16.17 (5.2)
Performance	8.83 (6.67)	11.25 (8.05)	7.08 (3.15)
Effort	14.33 (6.04)	13.67 (8.06)	12.33 (5.02)
Frustration	15.92 (8.03)	10.33 (5.37)	11.67 (5.79)

Appendix D.11: Weighted subscale by communication condition.



Appendix D.12 Study 1 – Pointing Results (Timing, Words, Events)

#	Timing	Words	Events
1	146	227	40
2	131	233	11
3	128	148	50
4	245	319	45
5	109	176	28
6	113	147	25
7	105	95	35
8	121	292	33
9	111	213	29
10	136	202	32
11	149	231	23
12	198	214	25
Sum:	1692	2497	376
Mean:	141.00	208.08	31.33
StdDev:	(41.4)	(61.87)	(10.47)

Appendix D.13 Study 1 – Pointing Results Workload Analysis: Mental Demand

	Mental Demand							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	4.00	19.00	5.07	2.00	4.00	0.53	23.00	5.60
2	4.00	20.00	5.33	2.00	5.00	0.67	25.00	6.00
3	3.00	12.00	2.40	4.00	1.00	0.27	13.00	2.67
4	3.00	12.00	2.40	4.00	1.00	0.27	13.00	2.67
5	5.00	15.00	5.00	2.00	5.00	0.67	20.00	5.67
6	5.00	13.00	4.33	2.00	4.00	0.53	17.00	4.87
7	4.00	5.00	1.33	2.00	10.00	1.33	15.00	2.67
8	4.00	4.00	1.07	2.00	7.00	0.93	11.00	2.00
9	5.00	15.00	5.00	4.00	5.00	1.33	20.00	6.33
10	5.00	13.00	4.33	2.00	4.00	0.53	17.00	4.87
11	4.00	5.00	1.33	4.00	10.00	2.67	15.00	4.00
12	4.00	4.00	1.07	4.00	7.00	1.87	11.00	2.93

Sum:	50.00	137.00	38.67	34.00	63.00	11.60	200.00	50.27
Mean:	4.17	11.42	3.22	2.83	5.25	0.97	16.67	4.19
StdDev:	(.72)	(5.68)	(1.77)	(1.03)	(2.9)	(.72)	(4.56)	(1.55)

Appendix D.14 Study 1 – Pointing Results Workload Analysis: Physical Demand

	Physical Demand							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	0.00	2.00	0.00	2.00	4.00	0.53	6.00	0.53
2	0.00	2.00	0.00	2.00	1.00	0.13	3.00	0.13
3	0.00	3.00	0.00	0.00	1.00	0.00	4.00	0.00
4	0.00	3.00	0.00	0.00	1.00	0.00	4.00	0.00
5	2.00	7.00	0.93	0.00	2.00	0.00	9.00	0.93
6	2.00	11.00	1.47	0.00	1.00	0.00	12.00	1.47
7	1.00	1.00	0.07	0.00	4.00	0.00	5.00	0.07
8	1.00	1.00	0.07	0.00	4.00	0.00	5.00	0.07
9	2.00	7.00	0.93	0.00	2.00	0.00	9.00	0.93
10	2.00	11.00	1.47	0.00	1.00	0.00	12.00	1.47
11	1.00	1.00	0.07	0.00	4.00	0.00	5.00	0.07
12	2.00	1.00	0.13	0.00	4.00	0.00	5.00	0.13
Sum:	13.00	50.00	5.13	4.00	29.00	0.67	79.00	5.80
Mean:	1.08	4.17	0.43	0.33	2.42	0.06	6.58	0.48
StdDev:	(.9)	(3.83)	(.59)	(.78)	(1.44)	(.16)	(3.12)	(.57)

Appendix D.15 Study 1 – Pointing Results Workload Analysis: Temporal Demand

	Temporal demand							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	1.00	9.00	0.60	2.00	15.00	2.00	24.00	2.60
2	1.00	1.00	0.07	2.00	1.00	0.13	2.00	0.20
3	3.00	8.00	1.60	4.00	1.00	0.27	9.00	1.87
4	3.00	7.00	1.40	4.00	1.00	0.27	8.00	1.67
5	2.00	8.00	1.07	1.00	13.00	0.87	21.00	1.93
6	2.00	11.00	1.47	1.00	4.00	0.27	15.00	1.73

7	3.00	1.00	0.20	3.00	4.00	0.80	5.00	1.00
8	3.00	15.00	3.00	3.00	8.00	1.60	23.00	4.60
9	2.00	8.00	1.07	1.00	13.00	0.87	21.00	1.93
10	2.00	11.00	1.47	1.00	4.00	0.27	15.00	1.73
11	4.00	1.00	0.27	3.00	4.00	0.80	5.00	1.07
12	3.00	15.00	3.00	3.00	8.00	1.60	23.00	4.60
Sum:	29.00	95.00	15.20	28.00	76.00	9.73	171.00	24.93
Mean:	2.42	7.92	1.27	2.33	6.33	0.81	14.25	2.08
StdDev:	(.9)	(4.91)	(.97)	(1.15)	(5.02)	(.63)	(8.14)	(1.32)

Appendix D.16 Study 1 – Pointing Results Workload Analysis: Performance

	Performance							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	3.00	2.00	0.40	4.00	1.00	0.27	3.00	0.67
2	3.00	3.00	0.60	4.00	1.00	0.27	4.00	0.87
3	5.00	2.00	0.67	4.00	1.00	0.27	3.00	0.93
4	5.00	0.00	0.00	4.00	1.00	0.27	1.00	0.27
5	3.00	11.00	2.20	3.00	7.00	1.40	18.00	3.60
6	3.00	3.00	0.60	3.00	3.00	0.60	6.00	1.20
7	4.00	3.00	0.80	4.00	15.00	4.00	18.00	4.80
8	4.00	15.00	4.00	4.00	6.00	1.60	21.00	5.60
9	3.00	2.00	0.40	3.00	4.00	0.80	6.00	1.20
10	2.00	4.00	0.53	3.00	3.00	0.60	7.00	1.13
11	3.00	3.00	0.60	4.00	6.00	1.60	9.00	2.20
12	3.00	5.00	1.00	4.00	5.00	1.33	10.00	2.33
Sum:	41.00	53.00	11.80	44.00	53.00	13.00	106.00	24.80
Mean:	3.42	4.42	0.98	3.67	4.42	1.08	8.83	2.07
StdDev:	(.9)	(4.27)	(1.09)	(.49)	(3.99)	(1.06)	(6.67)	(1.72)

Appendix D.17 Study 1 – Pointing Results Workload Analysis: Effort

	Effort							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R

1	2.00	9.00	1.20	5.00	15.00	5.00	24.00	6.20
2	2.00	10.00	1.33	5.00	1.00	0.33	11.00	1.67
3	1.00	4.00	0.27	2.00	3.00	0.40	7.00	0.67
4	1.00	5.00	0.33	2.00	2.00	0.27	7.00	0.60
5	3.00	10.00	2.00	4.00	16.00	4.27	26.00	6.27
6	3.00	8.00	1.60	4.00	2.00	0.53	10.00	2.13
7	2.00	5.00	0.67	5.00	10.00	3.33	15.00	4.00
8	2.00	5.00	0.67	5.00	12.00	4.00	17.00	4.67
9	1.00	10.00	0.67	2.00	8.00	1.07	18.00	1.73
10	3.00	8.00	1.60	4.00	4.00	1.07	12.00	2.67
11	2.00	5.00	0.67	3.00	8.00	1.60	13.00	2.27
12	2.00	5.00	0.67	3.00	7.00	1.40	12.00	2.07
Sum:	24.00	84.00	11.67	44.00	88.00	23.27	172.00	34.93
Mean:	2.00	7.00	0.97	3.67	7.33	1.94	14.33	2.91
StdDev:	(.74)	(2.37)	(.56)	(1.23)	(5.14)	(1.72)	(6.04)	(1.94)

Appendix D.18 Study 1 – Pointing Results Workload Analysis: Frustration

	Frustration							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	5.00	5.00	1.67	0.00	5.00	0.00	10.00	1.67
2	5.00	3.00	1.00	0.00	5.00	0.00	8.00	1.00
3	3.00	9.00	1.80	1.00	2.00	0.13	11.00	1.93
4	3.00	4.00	0.80	1.00	2.00	0.13	6.00	0.93
5	0.00	8.00	0.00	5.00	17.00	5.67	25.00	5.67
6	0.00	5.00	0.00	5.00	3.00	1.00	8.00	1.00
7	1.00	15.00	1.00	1.00	5.00	0.33	20.00	1.33
8	1.00	14.00	0.93	1.00	11.00	0.73	25.00	1.67
9	2.00	8.00	1.07	5.00	17.00	5.67	25.00	6.73
10	1.00	5.00	0.33	5.00	3.00	1.00	8.00	1.33
11	1.00	15.00	1.00	1.00	5.00	0.33	20.00	1.33
12	1.00	14.00	0.93	1.00	11.00	0.73	25.00	1.67
Sum:	23.00	105.00	10.53	26.00	86.00	15.73	191.00	26.27
Mean:	1.92	8.75	0.88	2.17	7.17	1.31	15.92	2.19
StdDev:	(1.73)	(4.59)	(.56)	(2.12)	(5.47)	(2.07)	(8.03)	(1.91)

Appendix D.19 Study 1 – Scaling Results (Timing, Words, Events)

#	Timing	Words	Events
2	86	183	6
2	54	126	12
2	69	166	3
2	59	147	13
2	89	183	16
2	53	98	8
2	78	213	10
2	48	97	16
2	77	152	16
2	83	197	21
2	81	175	15
2	76	118	8
Sum:	853	1855	144
Mean:	71.08	154.58	12.00
StdDev:	(14.12)	(38.27)	(5.15)

Appendix D.20 Study 1 – Scaling Results Workload Analysis: Mental Demand

	Mental Demand							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	4.00	13.00	3.47	3.00	4.00	0.80	17.00	4.27
2	4.00	3.00	0.80	3.00	5.00	1.00	8.00	1.80
3	5.00	12.00	4.00	4.00	11.00	2.93	23.00	6.93
4	5.00	14.00	4.67	4.00	7.00	1.87	21.00	6.53
5	4.00	3.00	0.80	5.00	4.00	1.33	7.00	2.13
6	4.00	10.00	2.67	5.00	15.00	5.00	25.00	7.67
7	2.00	3.00	0.40	2.00	11.00	1.47	14.00	1.87
8	2.00	3.00	0.40	2.00	2.00	0.27	5.00	0.67
9	4.00	3.00	0.80	5.00	4.00	1.33	7.00	2.13
10	4.00	10.00	2.67	5.00	15.00	5.00	25.00	7.67
11	2.00	3.00	0.40	2.00	11.00	1.47	14.00	1.87
12	2.00	3.00	0.40	2.00	2.00	0.27	5.00	0.67
Sum:	42.00	80.00	21.47	42.00	91.00	22.73	171.00	44.20

Mean:	3.50	6.67	1.79	3.50	7.58	1.89	14.25	3.68
StdDev:	(1.17)	(4.66)	(1.6)	(1.31)	(4.8)	(1.61)	(7.84)	(2.76)

Appendix D.21 Study 1 – Scaling Results Workload Analysis: Physical Demand

	Physical Demand							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	1.00	1.00	0.07	0.00	3.00	0.00	4.00	0.07
2	1.00	1.00	0.07	0.00	3.00	0.00	4.00	0.07
3	0.00	4.00	0.00	0.00	2.00	0.00	6.00	0.00
4	0.00	3.00	0.00	0.00	4.00	0.00	7.00	0.00
5	1.00	1.00	0.07	0.00	1.00	0.00	2.00	0.07
6	1.00	1.00	0.07	0.00	3.00	0.00	4.00	0.07
7	1.00	1.00	0.07	0.00	8.00	0.00	9.00	0.07
8	1.00	1.00	0.07	0.00	4.00	0.00	5.00	0.07
9	1.00	1.00	0.07	0.00	1.00	0.00	2.00	0.07
10	1.00	1.00	0.07	0.00	3.00	0.00	4.00	0.07
11	1.00	1.00	0.07	0.00	8.00	0.00	9.00	0.07
12	1.00	1.00	0.07	0.00	4.00	0.00	5.00	0.07
Sum:	10.00	17.00	0.67	0.00	44.00	0.00	61.00	0.67
Mean:	0.83	1.42	0.06	0.00	3.67	0.00	5.08	0.06
StdDev:	(.39)	(1.)	(.03)	(.)	(2.27)	(.)	(2.31)	(.03)

Appendix D.22 Study 1 – Scaling Results Workload Analysis: Temporal Demand

	Temporal demand							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	3.00	5.00	1.00	5.00	14.00	4.67	19.00	5.67
2	3.00	7.00	1.40	5.00	11.00	3.67	18.00	5.07
3	1.00	13.00	0.87	2.00	12.00	1.60	25.00	2.47
4	1.00	14.00	0.93	2.00	12.00	1.60	26.00	2.53
5	3.00	18.00	3.60	2.00	9.00	1.20	27.00	4.80
6	3.00	17.00	3.40	2.00	7.00	0.93	24.00	4.33
7	4.00	17.00	4.53	3.00	4.00	0.80	21.00	5.33

8	4.00	16.00	4.27	3.00	6.00	1.20	22.00	5.47
9	3.00	18.00	3.60	2.00	9.00	1.20	27.00	4.80
10	3.00	17.00	3.40	2.00	7.00	0.93	24.00	4.33
11	4.00	17.00	4.53	3.00	4.00	0.80	21.00	5.33
12	4.00	16.00	4.27	3.00	6.00	1.20	22.00	5.47
Sum:	36.00	175.00	35.80	34.00	101.00	19.80	276.00	55.60
Mean:	3.00	14.58	2.98	2.83	8.42	1.65	23.00	4.63
StdDev:	(1.04)	(4.29)	(1.49)	(1.11)	(3.29)	(1.22)	(2.98)	(1.09)

Appendix D.23 Study 1 – Scaling Results Workload Analysis: Performance

	Performance							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	2.00	3.00	0.40	4.00	10.00	2.67	13.00	3.07
2	2.00	2.00	0.27	4.00	7.00	1.87	9.00	2.13
3	2.00	1.00	0.13	5.00	7.00	2.33	8.00	2.47
4	2.00	3.00	0.40	5.00	6.00	2.00	9.00	2.40
5	2.00	1.00	0.13	2.00	6.00	0.80	7.00	0.93
6	2.00	13.00	1.73	2.00	15.00	2.00	28.00	3.73
7	5.00	1.00	0.33	4.00	6.00	1.60	7.00	1.93
8	5.00	1.00	0.33	4.00	5.00	1.33	6.00	1.67
9	2.00	1.00	0.13	2.00	6.00	0.80	7.00	0.93
10	2.00	13.00	1.73	2.00	15.00	2.00	28.00	3.73
11	5.00	1.00	0.33	4.00	6.00	1.60	7.00	1.93
12	5.00	1.00	0.33	4.00	5.00	1.33	6.00	1.67
Sum:	36.00	41.00	6.27	42.00	94.00	20.33	135.00	26.60
Mean:	3.00	3.42	0.52	3.50	7.83	1.69	11.25	2.22
StdDev:	(1.48)	(4.54)	(.57)	(1.17)	(3.59)	(.57)	(8.05)	(.93)

Appendix D.24 Study 1 – Scaling Results Workload Analysis: Mental Demand

	Effort							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R

1	2.00	8.00	1.07	2.00	6.00	0.80	14.00	1.87
2	2.00	5.00	0.67	2.00	10.00	1.33	15.00	2.00
3	3.00	15.00	3.00	3.00	11.00	2.20	26.00	5.20
4	3.00	14.00	2.80	3.00	13.00	2.60	27.00	5.40
5	1.00	2.00	0.13	3.00	6.00	1.20	8.00	1.33
6	1.00	7.00	0.47	3.00	15.00	3.00	22.00	3.47
7	3.00	2.00	0.40	3.00	2.00	0.40	4.00	0.80
8	3.00	5.00	1.00	3.00	4.00	0.80	9.00	1.80
9	1.00	2.00	0.13	3.00	6.00	1.20	8.00	1.33
10	1.00	7.00	0.47	3.00	11.00	2.20	18.00	2.67
11	3.00	2.00	0.40	3.00	2.00	0.40	4.00	0.80
12	3.00	5.00	1.00	3.00	4.00	0.80	9.00	1.80
Sum:	26.00	74.00	11.53	34.00	90.00	16.93	164.00	28.47
Mean:	2.17	6.17	0.96	2.83	7.50	1.41	13.67	2.37
StdDev:	(.94)	(4.45)	(.96)	(.39)	(4.36)	(.88)	(8.06)	(1.56)

Appendix D.25 Study 1 – Scaling Results Workload Analysis: Frustration

	Frustration							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	3.00	1.00	0.20	1.00	10.00	0.67	11.00	0.87
2	3.00	4.00	0.80	1.00	5.00	0.33	9.00	1.13
3	4.00	10.00	2.67	1.00	9.00	0.60	19.00	3.27
4	4.00	4.00	1.07	1.00	3.00	0.20	7.00	1.27
5	4.00	1.00	0.27	3.00	15.00	3.00	16.00	3.27
6	4.00	1.00	0.27	3.00	13.00	2.60	14.00	2.87
7	0.00	1.00	0.00	3.00	3.00	0.60	4.00	0.60
8	0.00	1.00	0.00	3.00	4.00	0.80	5.00	0.80
9	4.00	1.00	0.27	3.00	15.00	3.00	16.00	3.27
10	4.00	1.00	0.27	3.00	13.00	2.60	14.00	2.87
11	0.00	1.00	0.00	3.00	3.00	0.60	4.00	0.60
12	0.00	1.00	0.00	3.00	4.00	0.80	5.00	0.80
Sum:	30.00	27.00	5.80	28.00	97.00	15.80	124.00	21.60
Mean:	2.50	2.25	0.48	2.33	8.08	1.32	10.33	1.80
StdDev:	(1.88)	(2.7)	(.76)	(.98)	(4.94)	(1.11)	(5.37)	(1.18)

Appendix D.26 Study 1 – Mixed Results (Timing, Words, Events)

#	Timing	Words	Events
3	86	111	11
3	131	156	33
3	128	230	30
3	245	228	42
3	162	241	18
3	113	194	36
3	105	230	33
3	121	184	26
3	106	245	12
3	110	187	20
3	180	189	23
3	200	212	13
Sum:	1687	2407	297
Mean:	140.58	200.58	24.75
StdDev:	(46.92)	(39.16)	(10.23)

Appendix D.27 Study 1 – Mixed Results Workload Analysis: Mental Demand

	Mental Demand							
	Helper			Worker				
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	5.00	9.00	3.00	4.00	14.00	3.73	23.00	6.73
2	5.00	11.00	3.67	4.00	11.00	2.93	22.00	6.60
3	2.00	10.00	1.33	1.00	4.00	0.27	14.00	1.60
4	2.00	9.00	1.20	1.00	3.00	0.20	12.00	1.40
5	3.00	4.00	0.80	5.00	5.00	1.67	9.00	2.47
6	3.00	3.00	0.60	5.00	6.00	2.00	9.00	2.60
7	2.00	4.00	0.53	3.00	4.00	0.80	8.00	1.33
8	2.00	2.00	0.27	3.00	2.00	0.40	4.00	0.67
9	3.00	4.00	0.80	2.00	5.00	0.67	9.00	1.47
10	3.00	3.00	0.60	2.00	6.00	0.80	9.00	1.40
11	2.00	4.00	0.53	3.00	4.00	0.80	8.00	1.33
12	2.00	2.00	0.27	3.00	2.00	0.40	4.00	0.67

Sum:	34.00	65.00	13.60	36.00	66.00	14.67	131.00	28.27
Mean:	2.83	5.42	1.13	3.00	5.50	1.22	10.92	2.36
StdDev:	(1.11)	(3.32)	(1.09)	(1.35)	(3.58)	(1.14)	(6.08)	(2.09)

Appendix D.28 Study 1 – Mixed Results Workload Analysis: Physical Demand

	Physical Demand							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	0.00	1.00	0.00	0.00	2.00	0.00	3.00	0.00
2	0.00	1.00	0.00	0.00	3.00	0.00	4.00	0.00
3	0.00	11.00	0.00	0.00	4.00	0.00	15.00	0.00
4	0.00	11.00	0.00	0.00	3.00	0.00	14.00	0.00
5	0.00	1.00	0.00	0.00	3.00	0.00	4.00	0.00
6	0.00	3.00	0.00	0.00	2.00	0.00	5.00	0.00
7	0.00	1.00	0.00	1.00	0.00	0.00	1.00	0.00
8	0.00	1.00	0.00	1.00	0.00	0.00	1.00	0.00
9	0.00	1.00	0.00	0.00	3.00	0.00	4.00	0.00
10	0.00	3.00	0.00	0.00	2.00	0.00	5.00	0.00
11	0.00	1.00	0.00	1.00	0.00	0.00	1.00	0.00
12	0.00	1.00	0.00	1.00	0.00	0.00	1.00	0.00
Sum:	0.00	36.00	0.00	4.00	22.00	0.00	58.00	0.00
Mean:	0.00	3.00	0.00	0.33	1.83	0.00	4.83	0.00
StdDev:	(.)	(3.81)	(.)	(.49)	(1.47)	(.)	(4.78)	(.)

Appendix D.29 Study 1 – Mixed Results Workload Analysis: Temporal Demand

	Temporal demand							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	1.00	4.00	0.27	1.00	3.00	0.20	7.00	0.47
2	1.00	7.00	0.47	1.00	3.00	0.20	10.00	0.67
3	5.00	12.00	4.00	2.00	13.00	1.73	25.00	5.73
4	5.00	10.00	3.33	2.00	14.00	1.87	24.00	5.20
5	4.00	16.00	4.27	4.00	3.00	0.80	19.00	5.07
6	4.00	15.00	4.00	4.00	2.00	0.53	17.00	4.53

7	4.00	4.00	1.07	2.00	10.00	1.33	14.00	2.40
8	4.00	3.00	0.80	2.00	11.00	1.47	14.00	2.27
9	4.00	16.00	4.27	4.00	3.00	0.80	19.00	5.07
10	4.00	15.00	4.00	4.00	2.00	0.53	17.00	4.53
11	4.00	4.00	1.07	2.00	10.00	1.33	14.00	2.40
12	4.00	3.00	0.80	2.00	11.00	1.47	14.00	2.27
Sum:	44.00	109.00	28.33	30.00	85.00	12.27	194.00	40.60
Mean:	3.67	9.08	2.36	2.50	7.08	1.02	16.17	3.38
StdDev:	(1.3)	(5.48)	(1.72)	(1.17)	(4.76)	(.58)	(5.2)	(1.85)

Appendix D.30 Study 1 – Mixed Results Workload Analysis: Performance

	Performance							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	2.00	6.00	0.80	2.00	2.00	0.27	8.00	1.07
2	2.00	11.00	1.47	2.00	5.00	0.67	16.00	2.13
3	1.00	4.00	0.27	5.00	3.00	1.00	7.00	1.27
4	1.00	5.00	0.33	5.00	3.00	1.00	8.00	1.33
5	5.00	5.00	1.67	1.00	2.00	0.13	7.00	1.80
6	5.00	4.00	1.33	1.00	3.00	0.20	7.00	1.53
7	4.00	2.00	0.53	5.00	3.00	1.00	5.00	1.53
8	4.00	1.00	0.27	5.00	3.00	1.00	4.00	1.27
9	5.00	5.00	1.67	1.00	2.00	0.13	7.00	1.80
10	5.00	4.00	1.33	1.00	3.00	0.20	7.00	1.53
11	4.00	2.00	0.53	5.00	3.00	1.00	5.00	1.53
12	4.00	1.00	0.27	5.00	3.00	1.00	4.00	1.27
Sum:	42.00	50.00	10.47	38.00	35.00	7.60	85.00	18.07
Mean:	3.50	4.17	0.87	3.17	2.92	0.63	7.08	1.51
StdDev:	(1.57)	(2.72)	(.58)	(1.95)	(.79)	(.41)	(3.15)	(.3)

Appendix D.31 Study 1 – Mixed Results Workload Analysis: Mental Demand

	Effort							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R

1	4.00	6.00	1.60	3.00	8.00	1.60	14.00	3.20
2	4.00	11.00	2.93	3.00	14.00	2.80	25.00	5.73
3	5.00	11.00	3.67	4.00	4.00	1.07	15.00	4.73
4	3.00	10.00	2.00	4.00	4.00	1.07	14.00	3.07
5	2.00	6.00	0.80	2.00	3.00	0.40	9.00	1.20
6	2.00	3.00	0.40	2.00	3.00	0.40	6.00	0.80
7	4.00	2.00	0.53	0.00	10.00	0.00	12.00	0.53
8	4.00	3.00	0.80	0.00	10.00	0.00	13.00	0.80
9	2.00	6.00	0.80	5.00	3.00	1.00	9.00	1.80
10	2.00	3.00	0.40	5.00	3.00	1.00	6.00	1.40
11	4.00	2.00	0.53	0.00	10.00	0.00	12.00	0.53
12	4.00	3.00	0.80	0.00	10.00	0.00	13.00	0.80
Sum:	40.00	66.00	15.27	28.00	82.00	9.33	148.00	24.60
Mean:	3.33	5.50	1.27	2.33	6.83	0.78	12.33	2.05
StdDev:	(1.07)	(3.45)	(1.07)	(1.97)	(3.9)	(.84)	(5.02)	(1.75)

Appendix D.32 Study 1 – Mixed Results Workload Analysis: Frustration

	Frustration							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	3.00	1.00	0.20	5.00	12.00	4.00	13.00	4.20
2	3.00	8.00	1.60	5.00	13.00	4.33	21.00	5.93
3	2.00	14.00	1.87	3.00	1.00	0.20	15.00	2.07
4	4.00	11.00	2.93	3.00	2.00	0.40	13.00	3.33
5	1.00	3.00	0.20	3.00	5.00	1.00	8.00	1.20
6	1.00	3.00	0.20	3.00	4.00	0.80	7.00	1.00
7	1.00	7.00	0.47	4.00	12.00	3.20	19.00	3.67
8	1.00	1.00	0.07	4.00	4.00	1.07	5.00	1.13
9	1.00	3.00	0.20	3.00	5.00	1.00	8.00	1.20
10	1.00	3.00	0.20	3.00	4.00	0.80	7.00	1.00
11	1.00	7.00	0.47	4.00	12.00	3.20	19.00	3.67
12	1.00	1.00	0.07	4.00	4.00	1.07	5.00	1.13
Sum:	20.00	62.00	8.47	44.00	78.00	21.07	140.00	29.53
Mean:	1.67	5.17	0.71	3.67	6.50	1.76	11.67	2.46
StdDev:	(1.07)	(4.24)	(.92)	(.78)	(4.4)	(1.48)	(5.79)	(1.65)

Appendix D.33 Study 2 – Hybrid Results (Timing, Words, Events)

#	Timing	Words	Events
4	45	82	2
4	60	111	4
4	48	79	9
4	78	141	12
4	55	85	4
4	45	110	6
4	65	90	8
4	55	92	3
Sum:	451	790	48
Mean:	56.38	98.75	6.00
StdDev:	(11.26)	(20.85)	(3.42)

Appendix D.34 Study 2 – Hybrid Results Workload Analysis: Mental Demand

	Mental Demand							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	2.00	2.00	0.27	2.00	1.00	0.13	3.00	0.40
2	4.00	4.00	1.07	0.00	4.00	0.00	8.00	1.07
3	3.00	3.00	0.60	4.00	2.00	0.53	5.00	1.13
4	3.00	8.00	1.60	5.00	12.00	4.00	20.00	5.60
5	3.00	3.00	0.60	3.00	5.00	1.00	8.00	1.60
6	4.00	4.00	1.07	5.00	4.00	1.33	8.00	2.40
7	5.00	3.00	1.00	3.00	6.00	1.20	9.00	2.20
8	3.00	3.00	0.60	0.00	2.00	0.00	5.00	0.60
Sum:	27.00	30.00	6.80	22.00	36.00	8.20	66.00	15.00
Mean:	3.38	3.75	0.85	2.75	4.50	1.03	5.50	1.25
StdDev:	(.92)	(1.83)	(.42)	(1.98)	(3.46)	(1.32)	(5.18)	(1.66)

Appendix D.35 Study 2 – Hybrid Results Workload Analysis: Physical Demand

	Physical Demand							
	Helper			Worker				
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	0.00	2.00	0.00	0.00	1.00	0.00	3.00	0.00
2	0.00	2.00	0.00	5.00	4.00	1.33	6.00	1.33
3	0.00	1.00	0.00	2.00	1.00	0.13	2.00	0.13
4	1.00	4.00	0.27	0.00	1.00	0.00	5.00	0.27
5	0.00	3.00	0.00	1.00	1.00	0.07	4.00	0.07
6	1.00	4.00	0.27	2.00	2.00	0.27	6.00	0.53
7	1.00	2.00	0.13	3.00	2.00	0.40	4.00	0.53
8	1.00	2.00	0.13	0.00	2.00	0.00	4.00	0.13
Sum:	4.00	20.00	0.80	13.00	14.00	2.20	34.00	3.00
Mean:	0.50	2.50	0.10	1.63	1.75	0.28	2.83	0.25
StdDev:	(.53)	(1.07)	(.12)	(1.77)	(1.04)	(.45)	(1.39)	(.44)

Appendix D.36 Study 2 – Hybrid Results Workload Analysis: Temporal Demand

	Temporal demand							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	3.00	4.00	0.80	2.00	2.00	0.27	6.00	1.07
2	3.00	6.00	1.20	1.00	8.00	0.53	14.00	1.73
3	3.00	9.00	1.80	0.00	3.00	0.00	12.00	1.80
4	4.00	14.00	3.73	3.00	5.00	1.00	19.00	4.73
5	3.00	8.00	1.60	2.00	4.00	0.53	12.00	2.13
6	4.00	5.00	1.33	2.00	5.00	0.67	10.00	2.00
7	2.00	6.00	0.80	2.00	6.00	0.80	12.00	1.60
8	3.00	5.00	1.00	2.00	3.00	0.40	8.00	1.40
Sum:	25.00	57.00	12.27	14.00	36.00	4.20	93.00	16.47
Mean:	3.13	7.13	1.53	1.75	4.50	0.53	7.75	1.37
StdDev:	(.64)	(3.23)	(.96)	(.89)	(1.93)	(.31)	(3.93)	(1.13)

Appendix D.37 Study 2 – Hybrid Results Workload Analysis: Performance

	Performance							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	5.00	1.00	0.33	5.00	1.00	0.33	2.00	0.67
2	5.00	5.00	1.67	2.00	1.00	0.13	6.00	1.80
3	5.00	1.00	0.33	5.00	1.00	0.33	2.00	0.67
4	5.00	1.00	0.33	4.00	1.00	0.27	2.00	0.60
5	5.00	1.00	0.33	4.00	1.00	0.27	2.00	0.60
6	3.00	1.00	0.20	2.00	1.00	0.13	2.00	0.33
7	2.00	1.00	0.13	3.00	1.00	0.20	2.00	0.33
8	4.00	3.00	0.80	5.00	1.00	0.33	4.00	1.13
Sum:	34.00	14.00	4.13	30.00	8.00	2.00	22.00	6.13
Mean:	4.25	1.75	0.52	3.75	1.00	0.25	1.83	0.51
StdDev:	(1.16)	(1.49)	(.5)	(1.28)	(.)	(.09)	(1.49)	(.49)

Appendix D.38 Study 2 – Hybrid Results Workload Analysis: Effort

	Effort							
	Helper			Worker			Combined	
#	Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
1	1.00	2.00	0.13	4.00	2.00	0.53	4.00	0.67
2	2.00	4.00	0.53	4.00	3.00	0.80	7.00	1.33
3	3.00	6.00	1.20	1.00	2.00	0.13	8.00	1.33
4	2.00	12.00	1.60	1.00	12.00	0.80	24.00	2.40
5	3.00	6.00	1.20	2.00	5.00	0.67	11.00	1.87
6	2.00	5.00	0.67	2.00	4.00	0.53	9.00	1.20
7	3.00	7.00	1.40	3.00	5.00	1.00	12.00	2.40
8	1.00	3.00	0.20	4.00	2.00	0.53	5.00	0.73
Sum:	17.00	45.00	6.93	21.00	35.00	5.00	80.00	11.93
Mean:	2.13	5.63	0.87	2.63	4.38	0.63	6.67	0.99
StdDev:	(.83)	(3.07)	(.56)	(1.3)	(3.34)	(.26)	(6.28)	(.67)

Appendix D.39 Study 2 – Hybrid Results Workload Analysis: Frustration

Frustration							
Helper			Worker			Combined	
Weight	Rating	W/R	Weight	Rating	W/R	Rating	W/R
4.00	2.00	0.53	2.00	1.00	0.13	3.00	0.67
1.00	5.00	0.33	3.00	5.00	1.00	10.00	1.33
1.00	3.00	0.20	3.00	2.00	0.40	5.00	0.60
0.00	8.00	0.00	2.00	5.00	0.67	13.00	0.67
1.00	4.00	0.27	3.00	3.00	0.60	7.00	0.87
1.00	5.00	0.33	2.00	4.00	0.53	9.00	0.87
2.00	3.00	0.40	1.00	3.00	0.20	6.00	0.60
3.00	3.00	0.60	4.00	3.00	0.80	6.00	1.40
13.00	33.00	2.67	20.00	26.00	4.33	59.00	7.00
1.63	4.13	0.33	2.50	3.25	0.54	4.92	0.58
(1.3)	(1.89)	(.19)	(.93)	(1.39)	(.29)	(3.16)	(.32)