TECHNISCHE
UNIVERSITÄT
DARMSTADT

TRANSITIONS *in* MONITORING *and* NETWORK OFFLOADING

Handling Dynamic Mobile Applications and Environments

Vom Fachbereich Elektrotechnik und Informationstechnik
der Technischen Universität Darmstadt
zur Erlangung des akademischen Grades eines
Doktor-Ingenieurs (Dr.-Ing.)
genehmigte Dissertation

von

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Geboren am 26. April 1991 in Remscheid-Lennep

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Tag der Einreichung: 21. Januar 2019
Tag der Disputation: 5. April 2019

Hochschulkennziffer D17
Darmstadt 2019

Nils Richerzhagen, M.Sc.: *Transitions in Monitoring and Network Offloading,*
Handling Dynamic Mobile Applications and Environments
Darmstadt, Technische Universität Darmstadt,
Jahr der Veröffentlichung der Dissertation auf TUprints: 2019
Tag der mündlichen Prüfung: 05.04.2019

Bitte zitieren Sie dieses Dokument als: Please cite this document as:
URN: `urn:nbn:de:tuda-tuprints-86126`
URL: `http://tuprints.ulb.tu-darmstadt.de/id/eprint/8612`

ABSTRACT

COMMUNICATION demands increased significantly in recent years, as evidenced in studies by Cisco and Ericsson. Users demand connectivity anytime and anywhere, while new application domains such as the Internet of Things and vehicular networking amplify heterogeneity and dynamics of the resource-constrained environment of mobile networks. These developments pose major challenges to an efficient utilization of existing communication infrastructure.

To reduce the burden on the communication infrastructure, mechanisms for network offloading can be utilized. However, to deal with the dynamics of new application scenarios, these mechanisms need to be highly adaptive. Gathering information about the current status of the network is a fundamental requirement for meaningful adaptation. This requires network monitoring mechanisms that are able to operate under the same highly dynamic environmental conditions and changing requirements.

In this thesis, we design and realize a concept for transitions within network offloading to handle the former challenges, which constitutes our *first contribution*. We enable adaptive offloading by introducing a methodology for the identification and encapsulation of gateway selection and clustering mechanisms in the transition-enabled service AssignMe.KOM. To handle the dynamics of environmental conditions, we allow for centralized and decentralized offloading. We generalize and show the significant impact of our concept of transitions within offloading in various, heterogeneous applications domains such as vehicular networking or publish/subscribe.

We extend the methodology of identification and encapsulation to the domain of network monitoring in our *second contribution*. Our concept of a transition-enabled monitoring service AdaptMon.KOM enables adaptive network state observation by executing transitions between monitoring mechanisms. We introduce extensive transition coordination concepts for reconfiguration in both of our contributions. To prevent data loss during complex transition plans that cover multiple coexisting transition-enabled mechanisms, we develop the methodology of inter-proxy state transfer. We study the coexistence of offloading and monitoring within a collaborative location retrieval system for location-based services.

Based on our prototypes of AssignMe.KOM and AdaptMon.KOM, we conduct an extensive evaluation of our contributions in the Simonstrator.KOM platform. We show that our proposed inter-proxy state transfer prevents information loss, enabling seamless execution of complex transition plans that cover multiple coexisting transition-enabled mechanisms. Additionally, we demonstrate the influence of transition coordination and spreading on the success of the network adaptation. We manifest a cost-efficient and reliable methodology for location retrieval by combining our transition-enabled contributions. We show that our contributions enable adaptivity of network offloading and monitoring in dynamic environments.

KURZFASSUNG

Die Anforderungen an Kommunikationsnetze sind in den letzten Jahren deutlich gestiegen. Benutzer erwarten Konnektivität zu jeder Zeit und an jedem Ort. Neue Anwendungen wie das Internet der Dinge und die Vernetzung von Fahrzeugen, verstärken die Heterogenität und die Dynamik der mobilen Netze. Häufige Anforderungsänderungen, die Diversität der Netze und steigende Datenaufkommen stellen Kommunikationssysteme und -mechanismen vor große Herausforderungen.

Zur Entlastung der Netze können Offloading-Ansätze genutzt werden. Um jedoch mit der Dynamik neuer Anwendungsszenarien umgehen zu können, müssen diese Mechanismen sehr anpassungsfähig sein. Die Erfassung von Informationen über den aktuellen Zustand des Netzes ist eine grundlegende Voraussetzung für eine sinnvolle und effiziente Anpassung. Zur Erfassung sind dafür Monitoring-Mechanismen erforderlich, die in der Lage sind, unter den gleichen hochdynamischen Umgebungsbedingungen und wechselnden Anforderungen zu arbeiten.

In dieser Dissertation erforschen und realisieren wir ein Konzept für Transitionen innerhalb des Offloadings in Netzen, um die oben genannten Herausforderungen zu bewältigen. In unserem ersten Beitrag ermöglichen wir adaptives Offloading, indem wir eine Methodik zur Identifizierung und Kapselung von Gateway-Selektionsmechanismen und Mechanismen zum Clustering in unseren transitionsfähigen Dienst AssignMe.KOM einführen. Um der Dynamik der Umgebungsbedingungen gerecht zu werden, ermöglichen wir sowohl zentral als auch dezentral organisiertes Offloading. Wir generalisieren unser Konzept für heterogene Anwendungsbereiche wie Fahrzeugnetze und Publish/Subscribe-Systeme und zeigen die signifikanten Auswirkungen der Transitionen innerhalb des Offloadings.

In unserem zweiten Beitrag widmen wir uns der Erfassung der benötigten Zustandsinformationen in dynamischen mobilen Netzen. Unser Monitoringdienst AdaptMon.KOM ermöglicht eine adaptive Zustandsüberwachung des Netzes durch die Ausführung von Transitionen zwischen Monitoring-Mechanismen. In beiden Beiträgen führen wir umfangreiche Konzepte zur Koordination von Transitionen ein. Um Datenverlust bei komplexen Transitionsplänen zu vermeiden, die mehrere koexistierende, transitionsfähige Mechanismen betreffen, entwickeln wir die Methodik der proxyübergreifenden Zustandsübertragung. Wir untersuchen die Koexistenz von Monitoring und Offloading am Anwendungsfall der kollaborativen Standortbestimmung für ortsbezogene Dienste.

Basierend auf unseren Prototypen von AssignMe.KOM und AdaptMon.KOM führen wir eine ausführliche Evaluierung unserer Beiträge in der Simonstrator.KOM-Plattform durch. Wir zeigen, dass die proxyübergreifende Zustandsübertragung Informationsverluste verhindert und eine nahtlose Ausführung komplexer Transitionspläne ermöglicht. Darüber hinaus zeigen wir den Einfluss der Koordinierung und Verteilung von Transitionen auf den Erfolg der Netz- und Mechanismen-Adaption.

Durch die Kombination unserer transitionsfähigen Mechanismen ermöglichen wir eine kosteneffiziente und zuverlässige Standortbestimmung. Insgesamt zeigen wir, dass unsere Beiträge eine Adaption von Offloading und Monitoring an dynamische Umgebungsbedingungen und Anforderungen innerhalb des Netzes ermöglichen. Sie sind damit die Grundlage für adaptives Netzmanagement in zukünftigen Netzen.

DANKSAGUNG

Der *Weg ist das Ziel*, so hat es schon Konfuzius gesagt. Nach 36556 Stunden auf diesem Weg ist es nun also soweit, dass ein nächster großer Berg in Form der Dissertation bezwungen wird—oder bezwinge ich eher mich selbst, so wie es schon Edmund Hillary unmissverständlich darstellte? *Ist das nun das Ziel?* Ein klares "Jein–natürlich ist die Dissertation ein weiterer großer Haken auf der *Bucket List*, aber die hat zum Glück noch ein paar Seiten.

Auf den Gipfel zurückblickend und die langjährigen Anstrengungen in den Beinen fühlend, beflügelt die Gewissheit der erfolgreich abgeschlossenen Dissertation in der Tasche. Insgesamt blicke ich auf eine sehr spannende Zeit zurück. All das geht natürlich nicht allein, sonst hätte ich die Herausforderungen und Momente auf dem Weg nicht bewältigen und erleben können. Silvia, dir möchte ich für die Heranführung an die Forschungsarbeit, dein ausführliches Feedback, nicht nur während der Bachelorarbeit, und das Sähen des Promotionsgedankens ein herzliches Dankeschön nach Lugano schicken. Dominik, du hast trotz Zeitverschiebung und der ein oder anderen Nachtschicht immer das passende Feedback während meiner Masterthesis und auch danach während den Anfängen meiner Dissertation die nötige Ruhe Richtung Gipfel vermittelt. Ich möchte dir Ralf danken für die Möglichkeit an deinem Lehrstuhl promovieren zu dürfen—Danke! Andreas, danke für die großartige Zeit in Porto Alegre und Lancaster, das hat mir unglaublich viel gebracht, ebenso wie dein Feedback während der letzten Jahre. Ich wünsche dir viel Erfolg in Koblenz. Zum Glück arbeiten bei KOM keine Roboter, so war neben den überaus hilfreichen Diskussionen zur Forschung bei einer heißen Schoki, auf dem Flur oder auf dem Weg zum nächsten Meeting, immer Zeit für die soziale Komponente. Nicht nur im Kleinwalsertal konnten wir das ein oder andere isotonische Kaltgetränk genießen und über andere Dinge außerhalb der Arbeit philosophieren.

Mein Lieblings-Bürobuddy[1], danke für drei gemeinsame Jahre und die lockere Atmosphäre in unserem Büro. Danke für den *Tag des Müßiggangs* und das du dich auch nicht allzu ernst nimmst, was doch zu dem ein oder anderen Lacher geführt hat. Unter uns, das mit dem Skifahren solltest du an den Nagel hängen—ein Board unter den Füßen steht dir sicher besser, Alice meint das auch. Team 219 ist ohne Sonja aber nicht komplett, auch dir danke für die Starthilfe in den ersten Monaten und eine stehts ehrliche und offene Meinung. Patrick, in jeder noch so großen Katastrophe behältst du einen ruhigen Kopf—einfach eine coole Socke. Unsere gemeinsamen Diskussionen werde ich vermissen, genauso wie unsere Erfolge auf dem Widderstein im Kleinwalsertal oder im Olymp der *Kickergötter*. Tobias, *unser ewiges Kücken*, du gehst deinen Weg, da bin ich mir sicher. Danke für die spannende Zeit auf Kreta, in der KN II Vorlesung und bei allen sonstigen Veranstaltungen.

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[1] Der Mann für die besonderen Stunden ;)

Ich hatte das Glück außerordentlich motivierte Studenten betreuen zu dürfen. Sei es in Abschlussarbeiten, während Praktika, in Seminaren oder als HiWis—ich konnte mich immer auf die wertvollen und ergebnisreichen Diskussionen freuen. Danke an Jonas, Karsten, Michael, Max, Simon, Tim, Michal, Christoph, Marc und Clemens.

10 Jahre ist es bald her, dass wir uns als Ersties an der TU Darmstadt kennengelernt haben. Danke an euch (ich habe eh jemanden vergessen) Oli, Benni, Roland, Michael, Niko, Jan, Halis für die tolle Zeit während des Studiums aber auch danach.

Eine entsprechende Work-Life-Balance ist wichtig, Holger hat mir das schon im Studium wohlwollend beigebracht. Danke für die vielen Bouldersessions, die fingerkühlenden Getränke danach und stets das richtige Gespür für den ein oder anderen Spruch. Tim, was soll ich zu Tim sagen, ein herzenslieber Mensch. Danke für die gemeinsamen Momente in und um die Alpen—auf viele zukünftige Touren und Café Chaos Abende. Clemens, *auch ganz o.k.*, wie viel kann ein Mensch bitte essen? Ich bin immer wieder fasziniert von diesen Fähigkeiten, danke für die vielen gemeinsamen Urlaube und den Spaß, den wir dabei hatten. Und auch allen anderen Boulderern, sowie Jungs und Mädels der Darmstädter Dampfmaschinen, ein herzliches Danke für die tollen Stunden am Fels, Plastik und den gemeinsamen Momenten in den Wäldern und Bergen in und um Europa.

A Família, wie man so schön sagt. Daheim bei Mama und Papa ist es doch immer am schönsten. Die Unterstützung, aber auch das Verständnis den Jungen mal probieren zu lassen, sind sicher nicht einfach, aber für mich immer ein Fels in der Brandung, der mir den Rücken aus der Ferne im schönen Lennep freihält.

Wir wussten schon früh in Zürich, dass wir *wissenschaftliche Veranstaltungen* umsetzen können. Björn ist mehr als nur der große Bruder. Mal nebenher Dinge vollbringen die sonst drei Menschen in der doppelten Zeit erledigen—check. Ich kann mir kein besseres Vorbild vorstellen und bin stolz dein kleiner Bruder zu sein. Auf die tolle gemeinsame Zeit in der Bro-WG und bei KOM als Blues-Brothers, ich freue mich schon auf das was in der Zukunft kommt. Viel Erfolg bei deinen nächsten Schritten in München und Ingolstadt—ich bin mir mehr als sicher, dass ich mich entspannt zurücklehnen kann.

Schon vor der Promotion stets an meiner Seite, bin ich froh das wir uns gefunden haben. Die Chemie funktioniert einfach, im täglichen Leben und auf vielen gemeinsamen Reisen—es passt einfach. Du hast mich immer unterstützt und weißt, vielleicht schon erschreckend genau, wann Deine Aufmunterung von Nöten ist. Linda, Du bist die Beste. Ich freue mich auf alles was wir gemeinsam erleben werden sei es im Alltäglichen oder auf Reisen. Ich liebe Dich.

Merci und Danke!

CONTENTS

1

INTRODUCTION

The popularity of mobile devices—such as smartphones, tablets, and laptops—seems ever rising due to the extensive range of applications enabled by mobile broadband communication. According to Ericsson [61], the total number of mobile subscribers worldwide exceeded 5.3 billion in 2017 and is expected to exceed the 7.3 billion limit by the year 2023. Users have an *anytime, anywhere* mentality concerning mobile broadband communication and connection. In addition to the number of subscribers, the amount of traffic carried over 4G and 5G networks will increase at least 7-fold until 2021 according to Cisco [37].

Connectivity anytime, anywhere . . .

According to Ericsson [60], *i)* video streaming, *ii)* social networking, *iii)* web browsing, *iv)* over-the-air software updates, and *v)* audio take the largest shares of the occurring traffic. With a share of 55 % today and a predicted 75 % by 2023, video related traffic takes the most substantial part. Emerging fields such as the Internet of Things (IoT) or autonomous driving are not part of the study conducted by Ericsson [60] but are expected to produce vast amounts of data that is shared between billions of heterogeneous mobile and fixed devices [36, 38, 183]. As a result of this heterogeneous landscape of devices and usage scenarios, the dynamics observable in mobile networks are increasing significantly. In such dynamic environments the flexibility of the underlying network management plays an essential role to ensure stable operation.

. . . with smart devices as information sources.

The observable diversity in current and future mobile networks, the increasing traffic demand of the anytime, anywhere mentality of mobile users and increasing network and management needs pose major challenges to communication systems and mechanisms. Adapting a network requires information about the current state of the network. In today's mobile networks *i)* relevant monitoring data is imprisoned within single applications and not shared for a more extensive data basis and *ii)* there is no knowledge of the existence of the data in the network. The potential for collaboration of knowledge gained from different sources in the network remains largely unutilized. Efficient and reliable mobile network management requires mechanisms for dissemination and collection of information in the mobile network. These mechanisms need to operate in a resource-conserving way by offloading data over complementary wireless communication means wherever possible. The network management itself must adapt to the prior mentioned dynamics, too.

Surrounding dynamics . . .

. . . are challenges for monitoring . . .

. . . and network offloading.

To tackle the previously explained challenges and to provide for flexibility, we propose transition-enabled network offloading and monitoring services and their prototypical realization in this thesis. In the following, we motivate our approach to handle the dynamics of mobile applications and environments in network offloading and monitoring.

1.1 MOTIVATION FOR ADAPTIVE MONITORING AND NETWORK OFFLOADING

Monitoring as part of the MAPE-cycle

Network management is a core paradigm used for observation and adaptation decisions of networks and mechanisms [15, 39, 112]. An informed decision-making process is essential to allow for seamless functionality of, e. g., a network [15]. The core and omnipresent functionality of network management is split into four [40] or, depending on the model, five [101] phases. IBM models network management with the MAPE cycle [40]: *M*onitoring, *A*nalysis, *P*lanning, and *E*xecution. Kephart and Chess extend this with a *K*nowledge component resulting in the MAPE-K cycle. Other proposals basically depict the same idea [24, 55, 112, 126]. To handle the dynamics of mobile applications and environments, we place our focus on adaptive network offloading and application monitoring, which are deeply intertwined. Monitoring of a communication system can be divided into four phases [49–51, 91, 112, 122]: *measurement*, *collection*, *analysis* and *dissemination*. To pursue the goal of an adaptive transition-enabled monitoring service in this thesis, we focus on the measurement, collection, and dissemination efforts as they are affected by the dynamics of the communication system and applications. The analysis phase is usually done in a centralized fashion and therefore not directly affected by the aforementioned dynamics [15, 144].

Originating in the fixed networking domain [90, 182], several non-commercial [26, 58, 90, 165, 182] and commercial [3, 173, 180] monitoring solutions have been proposed, all aiming to observe and check the progress or quality of a process or a machine over a certain time. With increasing network complexity and heterogeneity, the research focus shifted from an *observe everything possible*, as in [76, 182], towards the scalability of the mostly centralized monitoring solutions. This scalability was achieved *i)* by a distribution of tasks to overcome single potential bottlenecks as in centralized approaches [14, 132, 144] and *ii)* by reducing the obtained amount of data to the necessary minimum [31, 50, 51].

Influence of mobility

With the rise of mobile networking, fixed network monitoring approaches were not applicable due to additional challenges such as intermittent connectivity and resource constrained devices. The proposed approaches obtain information with active measurements [14, 144, 170] or by passive observation [6, 98]. Today's solutions are specialized towards specific utility functions, such as robustness and reliability [144], distribution of overhead [31, 50, 51], timeliness of the information retrieval [14], or scalability [109, 143]. Three organizational structures emerged: *i)* centralized organization, with a single entity managing the monitoring effort and collection of data, *ii)* decentralized organization in which each client in the network takes a part of the whole monitoring effort, and *iii)* a mixture of both with hybrid organization approaches. For the last two, i. e. decentralized and hybrid, the assignment of roles to the clients in the network is an essential part [14, 15, 147]. This assignment of roles is equal to the efforts taken in the research domain of offloading [147]. Thus, mobile network monitoring requires the functionalities of offloading to handle changing application requirements and environmental conditions.

Need for offloading

While individual offloading and monitoring approaches pursue different utility functions, they share the specialization to a limited range of usage scenarios and often individual applications to improve the achieved performance. The narrow applicable field led to a degradation of the separation between monitoring approaches and monitored systems and applications. In today's heterogeneous mobile networks, fast-changing environmental conditions and requirements, such as available communication means, user density, and mobility, have a substantial impact on the efficiency of mechanisms and applications [41, 42]. As a result, the monitoring and offloading of mobile networks must be adaptive to handle the dynamics mentioned above.

Specialization for improved performance

The concept of offloading is understood as improving the flexibility of mechanisms by allowing the usage of different communication links to transfer data between source and destination. However, providing adaptivity within offloading approaches to adapt to network dynamics and changing requirements has not been considered in research. Also, in the area of network monitoring, adaptivity is either achieved by *i)* providing general monitoring solutions that lose granularity compared to specialized solutions [51, 132] or *ii)* by exchanging complete monitoring mechanisms during runtime, resulting in gaps in the achieved observation due to deactivation and startup.

Adaptive solutions required . . .

In recent years the research community created ideas towards more flexible systems to handle the increasing dynamics of current and future networking scenarios and to overcome the side effects of solutions that provide flexibility at the cost of high complexity. Mechanism transitions [67, 148, 200] proofed their benefit by overcoming the challenges mentioned above in different domains such as video streaming [167, 199, 201], publish/subscribe [148, 150], and others [67, 191].

. . . relying on mechanism transitions.

In this thesis, we address the challenges of widely applicable and environment independent monitoring and offloading mechanisms, that adapt to changes through transitions to handle the dynamics of applications and mobile environments.

1.2 RESEARCH CHALLENGES

Mobile networks and applications impose significant challenges on network monitoring and offloading mechanisms. The following research challenges have a strong influence on the design and development of transition-enabled monitoring and offloading for mobile networks.

Challenge: *Achieving anytime, anywhere connectivity and observability.*

Anytime, anywhere observability is essential for the monitoring of mobile users and applications. Both network offloading and monitoring require seamless connectivity of mobile users. Due to the strong interdependence with the user's location and the running applications, user mobility and the coverage of communication means are main impact factors for the efficiency of both domains [41, 42]. Those effects are amplified by the interaction patterns of mobile users due to, e. g., social factors, which result in group formations that must be considered. The adaptivity of the offloading and monitoring approaches determine to large extends the success of the seamless observation of the prevailing network and applications. Thus, in order to achieve the goals of this thesis, our proposed monitoring and offloading concept must be able to achieve seamless adaptivity to changing network conditions.

Challenge: *Heterogeneity and dynamics of mobile networks.*

A plethora of smart information sources of different characteristics, together with on-body or hand-held personal devices form a heterogeneous landscape of more or less relevant available information sensing devices. Changing environmental conditions and application requirements, multiplied by influences of user mobility, depict a scenario in which off-the-shelve network monitoring approaches reach their limitations. Combining local wireless on-demand and cellular or infrastructure-based communication improves efficiency concerning the load on the individual communication means. Especially for on-demand wireless networks, also referred to as Mobile Ad Hoc Networks (MANETs), the assignment of roles achieved by offloading solutions is crucial when used together with infrastructure-based communication networks. In such scenarios the selection of suitable *i)* measurement devices and *ii)* information collection and distribution entities is a significant challenge. Furthermore, the resulting service characteristics such as fairness strongly depend on the utilized selection strategy. Our proposed concept for transition-enabled monitoring and network offloading not only has to handle such challenges; to provide for superior performance it must take advantage of the heterogeneous mobile environment.

1.3 RESEARCH GOALS AND CONTRIBUTIONS

We show that the research challenges above can be addressed feasibly while considering the various aspects of the mobile environment. To address the research challenges above, the primary goal of this work is the development of *a concept for transitions within monitoring and network offloading* to handle the dynamics of mobile applications and environments, and, accordingly, the *design, implementation*, and *evaluation* of transition-enabled offloading and monitoring services. To achieve the primary goal, we pursue the following research goals in this thesis:

Research Goal 1: *Separation and encapsulation of mechanisms and functional components.*

To enable transitions within the domain of monitoring and offloading a classification of existing approaches is essential. The identification of main functional components of the different approaches allows for a separation of the monitoring mechanism and the monitored systems and the encapsulation in a transition-enabled design concept. Within the domain of monitoring we focus on *i)* the main *organizational schemes*, *ii)* the different communication approaches used for *collection and distribution* of relevant information, and *iii) position estimation approaches* for location-based services [153–155, 162]. For offloading, we focus on *gateway selection* and *clustering* strategies as these are the main components used within role assignment in communication mechanisms that combine local wireless on-demand and cellular or infrastructure-based communication [158, 161]. Both foci allow us to identify main building blocks for the encapsulation within the concept of the transition-enabled monitoring and network offloading services.

Research Goal 2: *Execution of mechanism transitions and decision spreading.*

Based on the identified main components and their encapsulation we allow for the execution of transitions in the domain of monitoring and offloading. Furthermore, based on the decision process and the transition type, i. e. which entity in the network decides on the transition, the decision must be spread in the network to the affected clients. Transitions allow for the usage of the respective most suitable mechanism at a time depending on environmental conditions and application requirements. During transitions, the state between the exchanged mechanisms can be transferred. As state may be relevant for other mechanisms, depending on the complexity of the transition, the possibilities for the transformation of state must be extended. Based on the successful integration of the transition methodology in research domains such as publish/subscribe and video streaming [67, 148, 167, 199, 201], we extend the approach of transitions to the domains of mobile network offloading and monitoring in this thesis. Our contributions to this methodology are the introduction of *i)* meaningful transition decision spreading concepts and *ii)* substantial state transfer possibilities. Thereby our focus lies on the execution environment for transitions within the domains of mobile network monitoring [153, 155, 159] and offloading [158, 161].

Research Goal 3: *Evaluation of mechanism transitions within monitoring and offloading.*

To assess the potential of transitions within mobile network monitoring and offloading we need to compare non-adaptive solutions with our contributions. We must consider the transition decision process and spreading to the affected clients here as well. Based on the exemplary use case of location-based services we examine the combined use and mutual dependency of our contributions. There we manifest a cost-efficient and reliable methodology for location retrieval in mobile networks by combining both transition-enabled mechanisms.

Security and privacy considerations

Proactive transition behavior

We focus on the mobile network with potentially on-demand local wireless networks and the edge network with infrastructure-based entities in this thesis. While the usability of our concepts is shown in this depicted scenario, they are also applicable to the wired core network [73–75]. While security aspects are not main focus of this thesis, state-of-the-art methods for the detection of intrusion [25, 207] or malicious clients [202] can be applied. The privacy of shared information must be protected in monitoring and offloading [35, 54, 128]. Considering the execution of transitions in communication systems, proactive execution based on prediction of the network status is a possible topic for future work.

1.4 STRUCTURE OF THE THESIS

This thesis is structured as follows. Chapter 2 provides the required background for monitoring and offloading in a mobile environment. We present and discuss the state-of-the-art on monitoring, offloading, and transition-enabled mechanisms in Chapter 3. We target the identified research gaps of the related work in Chapter 4 and Chapter 5, which constitute the main contributions of this thesis.

Offloading as a mean for traffic reduction and the assignment of roles is essential for the monitoring of dynamic mobile networks. AssignMe.KOM, as presented in Chapter 4, is a novel approach, which enables the usage of adaptive offloading concepts for a multitude of applications. The transition-enabled service allows for the dynamic usage of different offloading mechanisms under changing environmental conditions and system requirements. Thereby, AssignMe.KOM maintains the ability to pursue specific utility functions.

We detail the design of the transition-enabled monitoring service AdaptMon.KOM in Chapter 5. The identification and encapsulation of core monitoring functionalities allows for transitions between monitoring approaches. We rely on AssignMe.KOM for the essential selection of measurement entities and the assignment of tasks to allow for adaptive monitoring of dynamic environments. We detail the usage of coexistent transition-enabled services in the scenario of location-based services.

The in-depth evaluation of AssignMe.KOM and AdaptMon.KOM is presented in Chapter 6. We focus on the execution and impact of seamless transitions between monitoring mechanisms and transitions between gateway selection and clustering mechanisms. Additionally, we analyze the coexistence of transition-enabled mechanisms in both services. We combine AssignMe.KOM and AdaptMon.KOM to assess the dependencies and resulting characteristics of both services for the example of location-based services. We conclude this thesis with a summary of our core contributions in Chapter 7. Finally, we provide an outlook on potential future work.

2

BACKGROUND

In this chapter, we provide an overview on monitoring in mobile networking scenarios as motivated in Chapter 1. The scenario and its characteristics concerning the environment surrounding the user and used applications are detailed in Section 2.1. In Section 2.2 the structure and functionality of communication networks are explained. The concept of network monitoring including the definition of the term and the basics of monitoring in mobile networks are provided in Section 2.3. Section 2.4 details the concept of offloading and role assignment in (mobile) communication networks. This chapter concludes with the explanation of transitions used to provide adaptivity in communication networks in Section 2.5.

2.1 MOBILITY IN ENVIRONMENTS AND APPLICATIONS

The network, as considered in this thesis, comprises different mobile and non-mobile entities in an urban area. Mobile and non-mobile smart devices, such as IoT sensors or smartphones and tablets, depict the first class of entities. IoT sensors are mostly fixed in their position for environmental sensing and interaction or are attached to vehicles (taxis, buses, trams). The mobility patterns of those devices are predictable to large extends due to recurring routes [134]. Handheld devices such as smartphones are linked to the mobility pattern of the user. Due to the unpredictable movement behavior of humans, this is a significant influence factor on the communication possibilities achieved within mobile networks [16, 41]. Connectivity characteristics among clients and the availability of communication means are further affected by the mobility of humans and impose major challenges for communication mechanisms and applications [12]. Infrastructure-assisted entities such as Wireless Fidelity (Wi-Fi) Access Points (APs) and cellular towers form the backbone for the communication in the mobile network. As the focus of this thesis is on mobile networks, we assume any wired connection between, e. g., Wi-Fi APs and cellular towers to provide a reliable connection with zero loss and low latency. The mobile devices are constrained considering their available resources. Thus, there is a need for efficient consumption of resources within communication mechanisms, also considering non-functional requirements such as fairness of the resource consumption among the clients in the network.

Human mobility patterns

Effects on connectivity and communication

Resource constrained devices

In this thesis, we do not limit the general network monitoring aspects to a specific mobile networking scenario or application for reasons of universality. However, with a paradigm shift towards people-centric networking, the influence of the human on the communication characteristics gains importance [183]. Mobility, thus the location of a user in the network as introduced before, is a main influential factor and challenge for communication mechanisms and applications [12]. Consequently, parts of the contributions made in this thesis are within the domain of location-based services [108,

People-centric networking

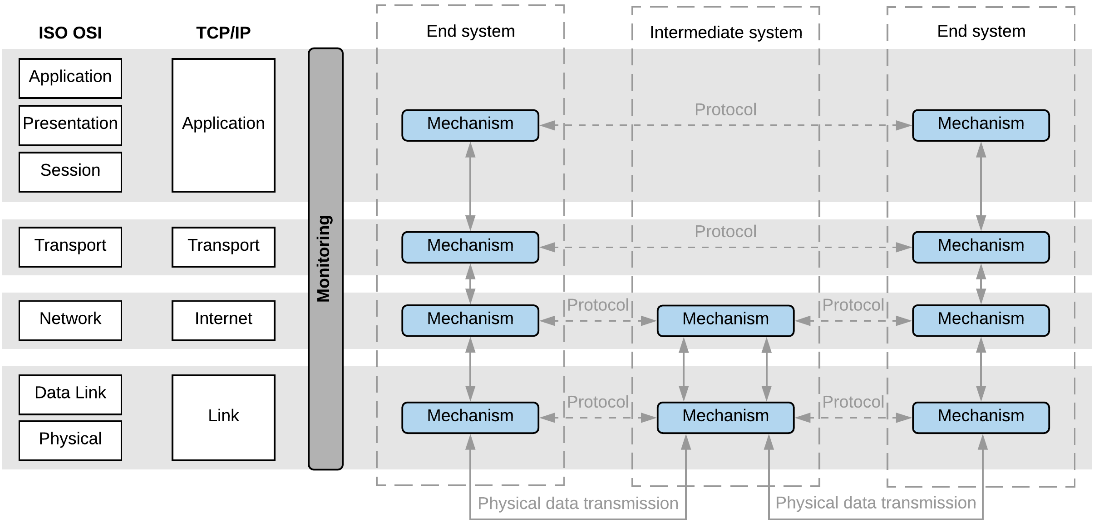


Figure 1: Layered communication models and data flow according to the ISO OSI [46, 211] and the TCP/IP model [23].

145]. The application field of location-based services is broad. Many location-based applications are recommendation systems for the user's surrounding [9]. Examples are additional information as obtained when using the search for "bus stop" or "ATM" in Google Maps and restaurant or amusement guides such as Tripadvisor [196] and Foursquare [64]. There are applications fields such as tracing services (e. g., for sales marketing [145]) that are mostly invisible to the user and result, for example, in personalized advertising. Emerging applications from the type of mobile augmented reality games, such as PokémonGo [133] and Google's Ingress [70], become increasingly important as those often also affect the user's mobility characteristics.

Locality and location-based services

2.2 COMMUNICATION NETWORKS

Communication networks are defined as the connection of a *set of end systems* through a *shared communication medium* via so-called *links* according to [193]. The Internet is a famous example of such a communication network, which we rely on in this thesis. Multiple reference models for protocol-based communication are defined in the literature. Those are the ISO/OSI reference model [46, 172, 211], the TCP/IP model [23] and the in this thesis used model by Tanenbaum and Wetherall [193]. The protocol-based communication in the reference model is based on a layered architecture as introduced by [46, 211]. Figure 1 shows this layered architecture including the data flow which we will explain in the following. As visible in the figure, there is *i)* direct communication between layers and *ii)* communication among end systems and intermediate systems (e. g. routers) using protocols.

Layered communication models

Protocols between end systems

Protocols allow for end-to-end communication between two mechanisms. This concept is also referred to as the *end-to-end principle*. However, this view is only valid within the protocol for the communication between two end systems, the underlying communication is, as visible in Figure 1 different. The communication process is going vertically through the different layers on the sending system and is using a physical data transmission between potentially multiple intermediate systems to reach the intended end system. On intermediate systems, the process is going up to the network or Internet layer where the routing of the data is performed.

Transparency between layers with services

The direct communication between adjacent layers on one system relies on *services* with well-defined functionalities, so-called *primitives*. The well-defined functionalities of the services guarantee compatibility among different mechanisms in a layer. Furthermore, due to the interface-based encapsulation of the services, the currently used mechanisms in a layer is transparent to the layers above and beneath. Throughout this thesis, we assume and model the Internet with given Quality of Service (QoS) attributes for the achievable latency, bandwidth, and reliability of end system connections. We handle cellular communication in the same way. The perception of the Internet and cellular communication as black box allows us to concentrate on the mobile networking part of the described contributions.

Core, edge, and mobile networks

Concerning communication networks, the research community distinguishes between the *i) core*, *ii) edge* and *iii) mobile* part. The core network interconnects subnetworks from Internet Service Providers and organizations such as Google and Facebook. Those networks rely on wired communication channels consisting of glass fiber optics allowing for high throughput and controlled communication. With high redundancy and over provisioning the core network provides a reliable communication with low failure probability. End-users do not participate in the core network.

From central control to . . .

. . . distributed flexibility and scalability.

Edge networks are the bridge between the wired core network and wireless mobile networks introduced afterwards. The entities of the edge network, e. g. public wireless APs, private households, cellular APs, are mostly connected through wires with the core network. In mobile networks end users are connected using a wireless communication medium such as Wi-Fi or cellular. Heterogeneity is very high in mobile networks due to the mobility of the clients, i. e. humans, and the diversity of the characteristics of the wireless communication. In contrast to edge and core networks, participants of mobile wireless networks are free to move, which poses additional challenges to operators of those networks and increases the failure probability. Infrastructure-less mobile networks, such as MANETs and Delay-tolerant Networks (DTNs), are a subpart of mobile networks [57, 185]. Those networks are characterized by relying only on on-demand or ad hoc device-to-device communication using the wireless medium. The usage of wireless communication imposes additional challenges, which result from the shared communication medium. Those challenges are, for example, the hidden terminal problem or partitions of the ad hoc network as shown in Figure 2.

Figure 2 shows the participants of a communication in a mobile network, beginning with the sender and receiver of information. Forwarding clients are used to carry information from sender to receiver(s). The sending range or communication range is strongly dependent on the surrounding, and the used communication means. In this thesis, as noted before, the focus of our contributions is in the domain of mobile and edge networks utilizing the core and infrastructure-based communication entities of the edge network as black boxes.

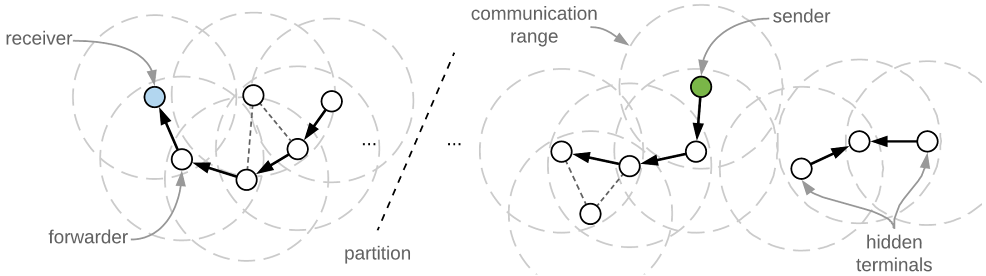


Figure 2: Visualization of the wireless communication principle with sender, receiver and forwarder. Additional challenges such as partition of communication islands and the hidden-terminal problem are shown.

Communication Patterns

The communication in the networks as mentioned earlier is concerning the patterns of different types. We mainly differentiate between the sending patterns *unicast*, *multicast*, and *broadcast*, which are visible in Figure 3. The unicast pattern describes communication between *one* sender and *one* (1 to 1) receiver at a time. This form of communication is still predominant in IP based networks like the Internet in which single entities communicate with each other. The File Transfer Protocol (FTP) and Hypertext Transfer Protocol (HTTP) employ TCP using unicast communication as visible in Figure 3a. The broadcast communication pattern describes the process of sending information from *one* sender to *all connected* (1 to 0..*) points in the network. Thus, all clients in the direct one-hop neighborhood to the sender as shown in Figure 3b. The Address Resolution Protocol (ARP) uses the broadcast communication pattern to send an address resolution query from the initiating entity to all entities in the local area network. The multicast communication pattern, visible in Figure 3c describes the sending of data from *one* sender to a *set* of receivers (1 to 0..*). This set of receivers can be an empty set, i. e. no receivers at all. The sending of TV channels is an excellent example of multicast-based communication. As the connection-oriented Transmission Control Protocol (TCP) is only supporting unicast, multicast mechanisms mostly rely on the connectionless User Datagram Protocol (UDP) transport protocol.

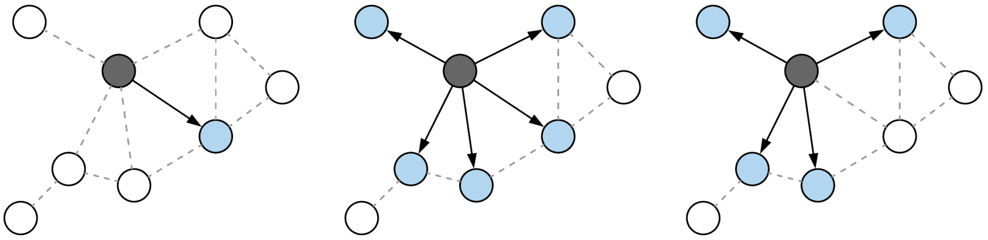
Unicast,

Broadcast,

and Multicast.

In mobile networks and infrastructure-less mobile networks, such as MANETs, all participants share the same communication medium. Due to its shared nature, communication in the wireless medium is broadcast-based. The consequence of this is that using the wireless communication medium increases the potential for collisions and information loss. The usage of the shared medium should be reduced to the necessary by mechanisms and applications to allow for the meaningful use of the available bandwidth. However, unicast or multicast behavior can be mimicked, by e. g. filtering on the receiving clients, and can increase the throughput rate due to so-called *supported rate* negotiations between sender and receiver resulting in a reduced usage time of the shared medium. Still, even with concepts such as supported rate negotiations, communication in wireless networks is based on broadcasts and thus adjacent clients do overhear any communication and cannot use the medium at the same time.

Shared medium in mobile networks



(a) Unicast: **one** to **one** (1 to 1)

(b) Broadcast: **one** to **all connected** (1 to 0..*)

(c) Multicast: **one** to **a set** (1 to 0..*)

Figure 3: Visualization of the communication patterns unicast, broadcast and multicast. Sending clients are highlighted in dark gray and receiving clients in light blue.

2.3 MONITORING IN COMMUNICATION NETWORKS

Network management is a core ingredient in the operation of networks [15, 39, 112, 171]. According to the ISO [172] there are five types of network management [171]: *i)* fault management, *ii)* accounting management, *iii)* configuration management, *iv)* performance management and *v)* security management. In this thesis, we focus on performance management of the underlying communication network including its mechanisms and applications. Battat et al. [15] formulate the need for monitoring in network management as follows: "monitoring is a network management function" with the purpose "to collect information such as the functional states of the participating clients and the operational states of the available routes". The monitoring of (mobile) communication networks includes the "reporting of the gained information to all participating clients or some of them according to the network application" [15]. The definition from Battat et al. [15] coincides with the definition of *to monitor* from the Oxford Dictionaries [49] as "observe and check the progress or quality of (something) over a period of time; keep under systematic review".

Monitoring a function . . .

. . . of network management.

Active and *passive* monitoring approaches are used to retrieve the desired information in the network. Overhearing of traffic is used in passive approaches [6, 98]. Active probing with, e. g. agents or by defined rules, is used in active monitoring [14, 144, 170]. Obviously, by introducing additional overhead and management effort, the results obtained by active monitoring are superior to passive approaches but at costs. In both, fixed and mobile networks, monitoring is perceived as a background task due to its indirect use [171]. Accordingly, monitoring should introduce as little overhead as possible - thus, there exists a trade-off between performance and cost of monitoring.

Passive and active measurements

IBM [40] describes network management with the MAPE cycle: *M*onitoring, *A*nalysis, *P*lanning, and *E*xecution. An extension of the MAPE cycle with a *K*nowledge component is proposed by Kephart and Chess in [101]. We divide monitoring similar to [49–51, 91, 112, 122] into four phases: *i)* measurement, *ii)* collection, *iii)* analysis and *iv)* dissemination. The analysis is part of both the MAPE cycle and monitoring, however

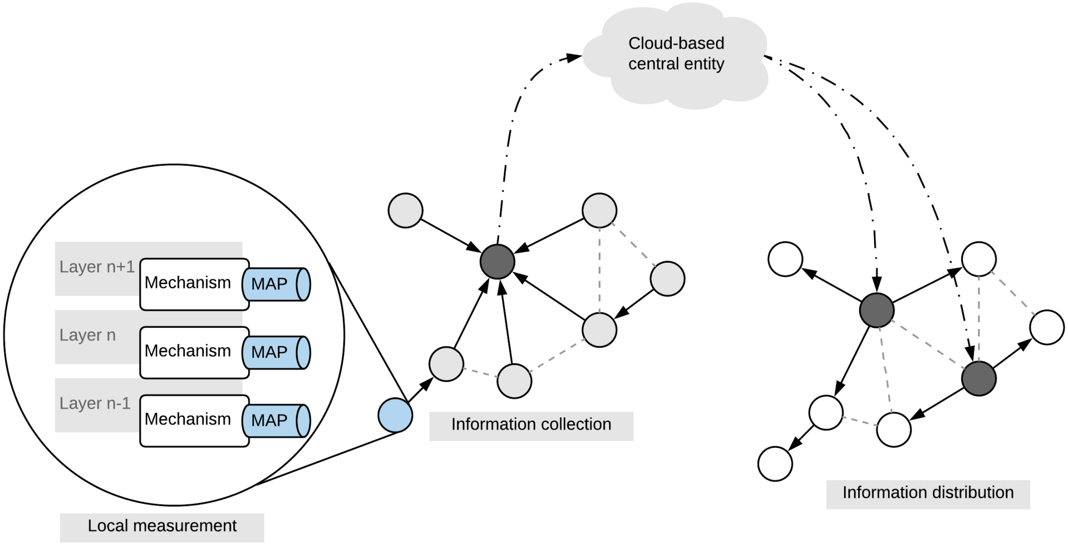


Figure 4: Visualization of the monitoring phases local measurement, information collection, and information dissemination.

within monitoring analysis is understood as the consideration of data obtained from the clients in the network to provide the requested information. In the MAPE cycle analysis is understood as the usage of the required information to plan for needed adaptations of the communication system. The measurement of information is done locally on the clients in the respective layers, as visible in Figure 4. The access of the respective layer and the multitude of possible mechanisms requires a vertical and horizontal cross-layered measurement. The cross-layered measurement of information is explained later in Chapter 5 of this thesis. In layered communication models, monitoring must be cross-layered to allow for information measurement from all layers and mechanisms as visible in Figure 1.

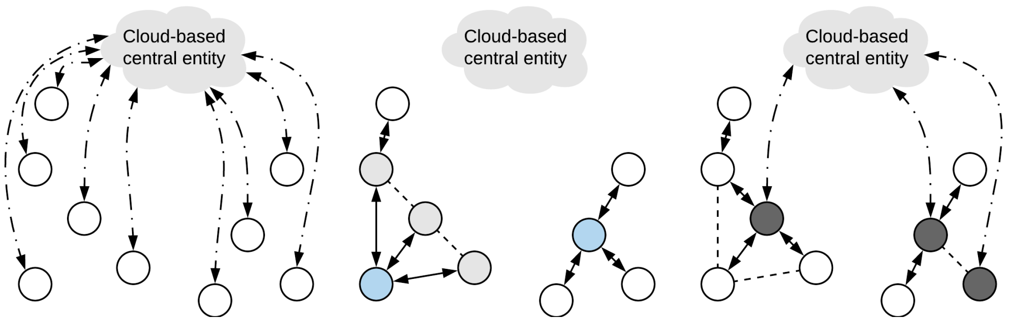
Cross-layered measurement

The collection and distribution of information in the network depend on *i)* the currently used monitoring topology and *ii)* the characteristics of the request posted to the monitoring. Details on the topological schemes used in monitoring follow later in this section. Due to the resource-constrained nature of the mobile devices both the collection and distribution must introduce as little overhead as possible in the sense of additional messages in the network and resources needed on the devices. At the same time, the results are mostly required in a timely and accurate manner, which may result in a conflict of interests concerning the overhead introduced by the approaches. Mobility, as highlighted in Section 2.1, poses additional challenges on the collection and distribution approaches in the mobile network and on-demand formed MANETs. Considering the goal of a transition-enabled monitoring service in this thesis, we focus on the measurement, collection and dissemination efforts as they are mainly affected by dynamics of the environment and applications.

Collection and distribution of information

Monitoring approaches are further characterized regarding their organizational structures concerning the used topology and the control organization [15, 112]. The topology of the approaches is classified as either *i)* centralized or *ii)* decentralized/dis-

Organization structures:



(a) Centralized topology (b) Decentralized topology (c) Hybrid topology

Figure 5: Organizational topology used in monitoring approaches.

tributed, while combinations of both are *iii)* hybrid approaches. Figure 5 shows the different topological structures within monitoring approaches. Centralized approaches use one, mostly cloud-based, entity in the network to collect and distribute the monitoring information to and from this point [22, 29, 30, 138]. In most approaches requests for information can only be queried at this one point [29, 30]. In centralized monitoring topologies, the roles of the clients in the network are limited to the measurement of the requested data and the direct reporting to the central entity, shown in Figure 5a. The clients in the network do not have further responsibilities. While the centrality allows for excellent control, scalability and reliability are challenging issues in such centralized structures due to the single point of failure.

Central, . . .

Decentralized or distributed monitoring approaches integrate the mobile clients stronger into the monitoring effort. The communication within these approaches is limited to the on-demand formation of MANETs without using cellular or other infrastructure-based communication means as visible in Figure 5b. All clients are available for information requests in those approaches. Clients collaborate with each other and exchange monitoring information in the mobile network to allow for needed redundancy of the data. The collaboration and exchange of information increase the potential scalability and reliability of decentralized monitoring systems. However, this comes at the cost of reduced control. Decentralized monitoring approaches find application in harsh environments such as post-disaster observation or when the cellular infrastructure is overloaded [14, 132, 163, 188, 190].

decentral, . . .

The trade-off between control and scalability or reliability is achieved with hybrid topologies. Hybrid monitoring approaches rely on infrastructure-assisted centralized parts in combination with decentralized, mostly on-demand, communication topologies in the mobile network. This combination, visible in Figure 5c, increases the control achieved in the approach compared to decentralized solutions. At the same time, scalability and reliability are higher compared to the centralized approaches.

. . . and hybrid.

In both hybrid and decentralized monitoring topologies the organization of the clients is either of flat [190] or of hierarchical [14, 132, 144, 188] nature. For the organization of hierarchical approaches, the selection and assignment of roles for the clients are essential. Based on the assignment of roles to the mobile clients, the collection and distribution of monitoring information are affected significantly. Details on the assignment of roles, a part of offloading, are given in Section 2.4.

Challenges of mobile network monitoring

According to [6, 15, 144] several challenges arise for monitoring services in mobile networks. We introduce those in the following briefly. Fault-tolerance or *robustness* is vital within monitoring as, e. g., any collected data should not get lost if a connection is dropped due to client mobility. Accordingly, to provide for robustness a *distribution of the load* on the clients for the stored information and the control overhead must be reached. Single points of failure, thus a centralized control, are to avoid if possible. The distribution of the organization allows for a certain continuity of the monitoring service. *Scalability*, as already discussed, is an essential characteristic for the monitoring. Due to mobility, density fluctuations are very likely, and the monitoring service must be able to cope with such changes. In the organization of the monitoring approach *device heterogeneity* is a main influential factor that must be considered. Not all devices are capable or at least suitable for specific tasks that require, e. g. a dense neighborhood or high bandwidth connectivity. Concerning the dynamics of the mobile environment, as discussed in Section 2.1, *adaptability* of the monitoring service to the surrounding and the requirements posted is needed. The monitoring service itself must be able to retrieve the requested information as fast as possible (*timeliness*) and at a high *accuracy*. In combination with the *low footprint* requirement of the background service, the introduced costs, such as bandwidth and energy consumption on the resource-constrained mobile devices, must be low. More challenges concerning security rise, which are not in the scope of this thesis. We refer the interested reader to [15].

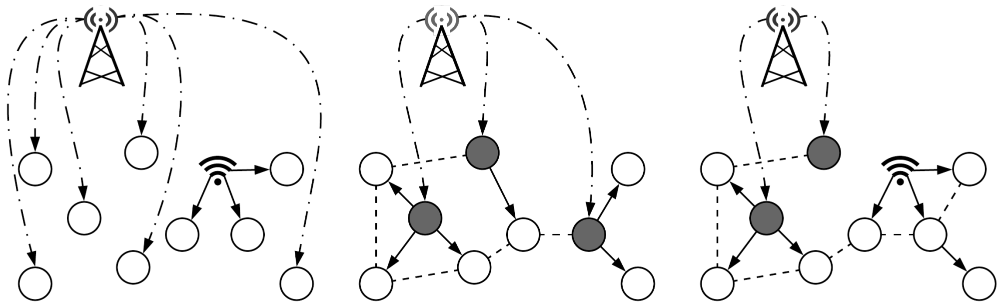
Mechanisms, protocols, and applications can be monitored in a communication network beside environmental factors. For better readability, we refer to all of the former as *monitored mechanisms* in this thesis.

2.4 OFFLOADING AND ROLE ASSIGNMENT IN COMMUNICATION NETWORKS

To handle increasing network load different approaches exist. Mobile operators throttle the connection speed and cap the data usage for their customers [45]. Throttling connection speed, however, is conflicting with customer satisfaction goals, the development of mobile broadband usage, and contradicting to the anytime and anywhere mentality users demand on their connectivity status. In recent years the approach of offloading data through the unused bandwidth of different wireless communication technologies gained importance.

Combining complementary wireless technologies

Rebecchi et al. [147] define offloading as "using a complementary wireless technology to transfer data originally targeted to flow through the cellular network". In other words, offloading is the combined usage of cellular infrastructure-based communication and wireless (on-demand) communication, such as in MANETs or Wi-Fi assisted networks. The literature often refers to this as terminal-to-terminal or device-to-device communication [147, 208]. The offloading of traffic to wireless (on-demand) networks includes the potential for a significant reduction of the traffic load on the cellular network [52]. There are four main offloading schemes defined in the literature [147, 208], which we show in Figure 6 for better understandability: offloading *i)* through



(a) Offloading through Wi-Fi networks (b) Offloading through opportunistic networks (c) Offloading through heterogeneous networks

Figure 6: Visualization of the offloading schemes used in mobile networks to reduce the load on the cellular network.

small cells, *ii)* through Wi-Fi networks, *iii)* through opportunistic mobile networks and *iv)* through heterogeneous networks. It is important to highlight that other than shown in Figure 6 the communication could also be directed away from the clients.

Different offloading schemes

Offloading through small cells is mainly the distribution of the cellular load to smaller cells. As this approach is not considering a different wireless communication technology [147] we focus on the other three offloading schemes in this thesis. Offloading through Wi-Fi networks describes the process of using (public) Wi-Fi APs for the transmission of data, as visible in Figure 6a. Utilizing only a selected subset of clients for cellular connection and relying on the distribution of the data to the other clients using a local on-demand network describes offloading through opportunistic mobile networks (see Figure 6b). For that, the selection and eventually the clustering of the clients in the mobile network is essential to select the most suitable candidates to use their cellular connection. The local on-demand communication is often based on Wi-Fi ad hoc or Bluetooth.

The offloading through heterogeneous networks describes a hybrid form of offloading through Wi-Fi and opportunistic networks. Thus, as visible in Figure 6c some data is sent over the cellular network to a fraction of the clients and some data through (public) APs to another fraction of clients. Both receiving subsets of clients further distribute the received data in their proximity using local on-demand communication.

Gateway selection and clustering

To enable the offloading through the usage of opportunistic mobile networks or heterogeneous networks most approaches rely on the selection of gateways and the clustering of the clients in the network. We refer to this gateway selection and clustering as role assignment. This assignment of roles is essential as the connectivity characteristics, thus the resulting communication possibilities, are mainly influenced by the mobility and location of the respective clients (see Section 2.1). We will detail the current state-of-the-art gateway selection and clustering approaches used in offloading in Section 3.2. Both, the selection of gateways and the clustering of clients can be based on a central or on a decentralized approach. A distinctive characteristic of gateway selection approaches is the pursued utility function. Many approaches focus on the achieved cost savings for the device resources used or regarding the cellular network traffic reduction [146, 209]. Other approaches focus on the Quality of Experience (QoE) such as availability and the achieved throughput [85, 118]. Robustness against network dynamics such as mobility and the fairness of the offloading or gateway selection process is the utility for a few approaches [86, 114]. Many try to incorporate combined weighted metrics to cover multiple utility functions. However, those approaches are often difficult to operate due to many possible adjustments [28, 84]. The challenge with the needed specification of the selection approaches is the resulting inflexibility when the requirements for the selection change over time.

Clustering of mobile clients

Clustering in mobile networks is differentiated into four main categories, which perform the clustering either based on *i)* density, *ii)* partitions, *iii)* hierarchies or *iv)* cells. We briefly introduce the different clustering schemes in the following, while more details on the specific related work in this area will be given in Section 3.2. Density is a measure for the proximity of clients. Accordingly, density-based clustering aims to establish clusters in which the density is significantly higher compared to the density in between the clusters [106].

Partition-based clustering relies on a given number k to partition the network into k cluster. Depending on the computation criteria of the clustering algorithm the clients are (re-)assigned in the different clusters until an optimal solution is found. In this case, the optimum refers to the characteristics of the algorithm.

Hierarchical clustering approaches establish a complete hierarchy, i. e. all layers in the hierarchy from one cluster per client to one cluster for all clients are computed. Hierarchical clustering is split into agglomerative and divisive approaches. As the name suggests, agglomerative approaches follow a bottom-up strategy. Thus, from the initial one cluster per client starting point, two clusters are connected if the distance in between is the shortest observable. Depending on the distance measure different clusters arise after the computation of all distances between all clusters. Divisive approaches pursue a top-down strategy. Beginning with one cluster consisting of all clients this cluster is split until all clients are an individual cluster. One approach is the Divisive Analysis (DIANA) by Kaufman and Rousseeuw [96]. In DIANA those clients with the highest inequality are removed from the cluster first. For each removed client a cluster is established to which all clients that have a shorter distance to the newly established cluster than to the old one are shifted. Out of complexity reasons divisive strategies $\mathcal{O}(2^{n-1})$ are used less often compared to agglomerative strategies $\mathcal{O}(n^3)$ [63]. Both hierarchical clustering approaches can be terminated at any point in time delivering a valid result, which can be sensible if a termination criterion such as the maximum number of clusters to be built is reached.

Cell-based clustering approaches divide an area into multiple cells. Each cell has, according to the current approach, given characteristics. Based on those, the clients are assigned to the most suitable cell, for which the densities are calculated afterwards when all clients are assigned. Cells that do not meet a previously defined density threshold are merged with adjacent cells. These merged cells represent the clusters later. As detailed in Section 2.3, the organization of hierarchical monitoring approaches is depending on the assignment of roles for the mobile clients. We con-

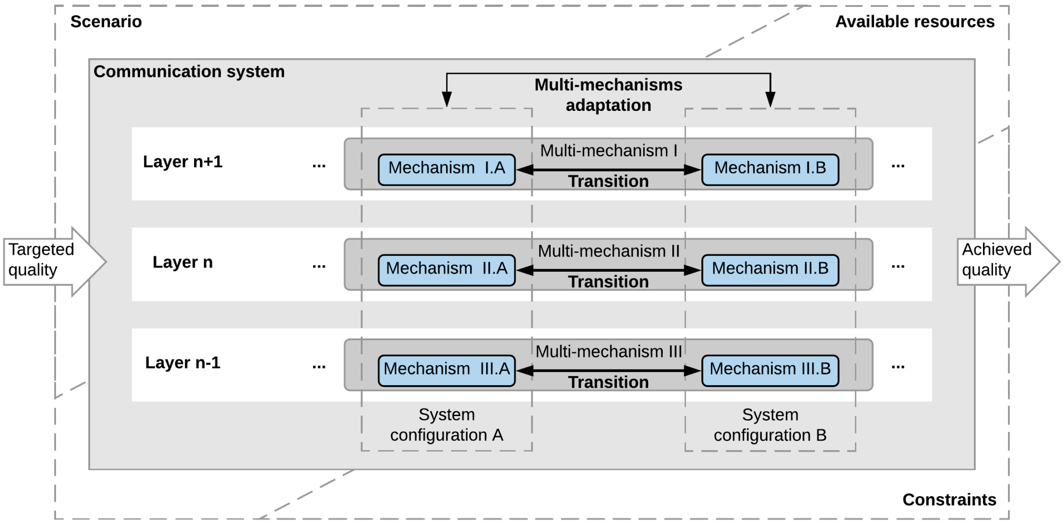


Figure 7: Multi-mechanisms adaptation in a communication system by executing transitions between mechanisms on different layers. Based on the work done in the Collaborative Research Centre "MAKI".

sider the offloading through role assignment, i. e. gateway selection and clustering, in dynamic networks on its own in this thesis in Chapter 4. However, due to the nature of hybrid and decentralized monitoring approaches, we also target a joint consideration of monitoring and offloading in item 5.5.

2.5 ADAPTIVITY THROUGH TRANSITIONS

Transitions of Multi-mechanisms

Adaptivity of systems and mechanisms in advanced networking scenarios gains in importance due to the increasing presence of dynamics and heterogeneity. Flexible systems that allow *i)* the handling of the increasing dynamics in current and future networking scenarios and *ii)* to overcome the side effects of solutions that provide flexibility by losing required unique features have been proposed in recent years. Transitions between mechanisms, as shown in Figure 7 and described in [2, 67, 148, 200], proofed their benefit by overcoming the challenges mentioned above. The beginning of the research on transitions has been conducted in different domains, such as video streaming [167, 199, 201], publish/subscribe [148, 150], and others [2, 67, 191]. In the following, we provide the details on transitions beginning with the categorization of the former in the communication system and the definition of transitions.

The earlier introduced multitude of potential application scenarios, available resources, and the constraints a communication system encounters lead to the development of many functionally related mechanisms[1], so-called multi-mechanisms[2] in the context of the Collaborative Research Centre "MAKI", as visible in Figure 7. A transition as a tool for the adaptation of the communication system to, e. g., changing

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[1] Mechanism: a functionality of the communication system, i. e. part of a protocol
[2] Multi-mechanism: a set of mechanisms of related/similar functionality

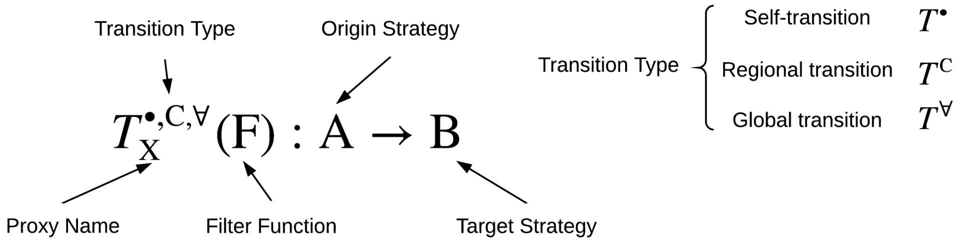

Figure 8: Definition of a transition based on previous work done in Collaborative Research Centre "MAKI" [67, 148, 155].

constraints relies on the exchange of (multiple) mutually dependent mechanisms on different layers of the communication stack. By switching between system configurations, as shown in Figure 7, transitions allow the communication system to achieve the desired quality even under the aforementioned challenges such as dynamic scenarios or changing constraints. Considering the coexistence of a plurality of such multi-mechanisms additional challenges, such as the shared usage of the available resources and interdependencies between the multi-mechanisms, arise.

For the definition of the transition, we rely on the notion of a proxy, which is the encapsulation of functional similar mechanisms to a well-defined interface. Proxies ensure that the used mechanisms are transparent behind the proxy and that basic required functionalities are supported among different mechanisms when executing transitions. A transition on proxy X, targeting a set of clients C $(C \subset \{c_1, c_2, c_3, ...c_n\})$ between an origin strategy A and a target strategy B is written the in following $T_X^C : A \to B$. Figure 8 shows the ingredients of the transition definition. Additionally, to specify the targeted clients more clearly a filter function F can be used.

Proxies to encapsulate functionality of similar mechanisms

To prevent the loss of relevant information and to ameliorate the start of the target strategy B within the life cycle of a transition we rely on the concept of *intra-proxy state transfer*, as defined in [67, 148]. Figure 9 shows the life cycle of the transition between mechanisms A and B and the intra-proxy state transfer. According to the definition, state transfer must not include any additional communication as otherwise the atomicity of transitions cannot be guaranteed [67, 148]. State that may be transferred between two mechanisms of a multi-mechanism is annotated as follows.

```
@TransferState(value = { "FieldValue" })
```

In this example, the state of `FieldValue` is transferred from mechanism A to mechanism B using the `setFieldValue` method that must be provided by both mechanisms.

Depending on the current network situation a single transition might not be sufficient to adapt to the dynamics correctly. In such cases transitions are concatenated in so-called *transition plans*. The execution order of the transitions in the plan is defined on creation, ensuring that clients in the network perform the same actions. As state transfer is bound to a single transition, some information might be lost during wide-reaching reconfigurations achieved with transition plans. To overcome this information loss, we introduce the inter-proxy state transfer in Section 5.4.

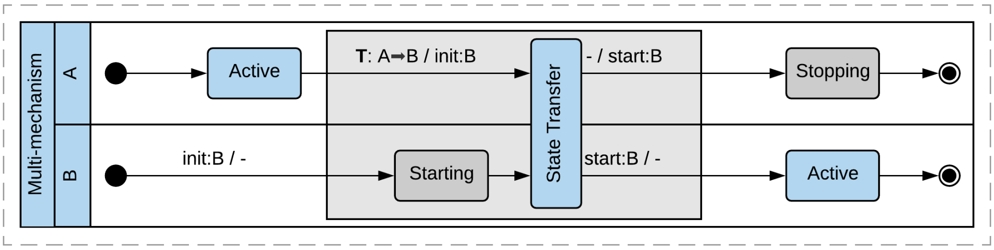

Figure 9: Illustrated life cycle of a transition with intra-proxy state transfer between the two mechanisms *A* and *B* of the exemplary multi-mechanism [148].

Different transition types

We distinguish three types of transitions concerning their scope as visible in Figure 8. Those types are *i)* the *self-transition*, *ii)* the *regional transition*, and *iii)* the *global transition*. The self-transition $T^{\bullet}$ is only targeting the initiating client itself. It is used to initiate parameter adaptations on the clients or local adaptation to the prevailing network conditions. Regional transitions T^{C} target a specified group of clients *C* $(C \subset \{c_1, c_2, c_3, ...c_n\})$ that match with the optional filter function *F*. Global transitions $T^{\forall}$ target all clients in the network. By relying on the optional filter function *F* the targeted clients can be specified in greater detail. For both regional and global transitions, the spreading of the transition decision is relevant and an essential part for the success of the transition in the network. Up to now, Client/Server (C/S) approaches have been considered for the spreading of the transition decision [148, 167, 199]. All are assuming a reliable spreading of the transition decision in the network to the targeted clients. Self-healing approaches are used to overcome potential incompatibilities by synchronizing transition decisions among clients in dynamic environments [148, 155].

3

STATE OF THE ART

We provide a detailed overview and discussion of the relevant research fields and the respective approaches in this chapter. We use the organizational structures of the state-of-the-art monitoring solutions as structure for our discussion in Section 3.1. Furthermore, Section 3.1 highlights systems for location-based services, i. e. position estimation techniques, and collaborative monitoring strategies. We discuss offloading approaches in mobile networks in Section 3.2. We split the research area of offloading for the detailed discussion into gateway selection and clustering strategies. In Section 3.3, we highlight how adaptivity has been achieved using transitions in communication systems so far. Section 3.4 concludes this chapter with a summary of the discussions, open challenges, and how we target those in this thesis.

3.1 MONITORING IN MOBILE NETWORKS

Most of the primary management and monitoring protocols focus on the monitoring of end-to-end connections assuming reliable connectivity. As some approaches explained in the following are based on these protocols, we briefly introduce those protocols in the following. The Simple Network Management Protocol (SNMP) [182] collects and modifies information on devices in IP-based networks. SNMP uses a so-called Management Information Base (MIB), which represents data in the form of variables. Applications can query for the variables to obtain information from SNMP. The Internet Control Message Protocol [90] is used in IP-based networks to send error or operational information messages. Messages, directed to the source of the originating packet, can indicate that they are unavailable or unreachable. NETCONF [58, 165] and CAPWAP [26] are used for the configuration of network devices and wireless APs.

Passive & active monitoring

Kazemi et al. [98] and Badonnel et al. [6] present two passive monitoring approaches. MMAN [98] is a non-intrusive monitoring solution, which introduces no additional traffic in the used communication medium of the ad hoc network. While MMAN relies on the passive observation of the network with *monitoring units*, the information collected is sent using a different wireless communication technology than the observed ad hoc network uses. Badonnel et al. [6] propose a customization of SNMP [182] with a MIB for ad hoc networks. To construct a network view, the authors use a two-tiered architecture, in which probes overhear and analyze messages in the network and report their findings to a central manager using the MIB. Passive approaches cannot provide the same level of details on the current network state. Active approaches introduce additional overhead and management efforts, but the results obtained are superior to passive approaches considering the information content. We focus on active monitoring approaches in the following.

Based on the introduction of network monitoring as part of the management process in Section 2.3, we divide the discussion of the state-of-the-art monitoring approaches into the organizational structures according to [15, 112]. Thus, we discuss *i)* centralized, *ii)* hybrid, and *iii)* decentralized/distributed approaches in the following.

3.1.1 *Centralized Strategies*

Excellent control

Centralized approaches rely on a central entity in the network to collect and distribute the monitoring information. No local on-demand wireless communication is used. This single instance calculates statistics based on the received information. These approaches solely rely on the communication of the local clients, i. e. smartphones or sensors, and the central entity using direct cellular or Wi-Fi communication. There are many approaches of commercial nature such as the solutions from SevOne[1] and Qosmotec[2]. ChukWa [22], CoMon [138] and Jigsaw [29, 30] are examples of centralized approaches originating from the research community.

Limited scalability

Centralized monitoring approaches mostly limit the roles of clients in the network to the measurement of requested data and direct reporting to the central entity. Information requests can only be queried at the central point [29, 30]. Centralized monitoring strategies allow for excellent control, but challenges such as scalability and reliability are predominant due to the single point of failure. In today's and future networking scenarios, such as IoT and opportunistic mobile social networks, where local interconnectivity among users and communication with sensing entities such as environmental sensors is essential, centralized monitoring strategies are limited.

3.1.2 *Hybrid Strategies*

Combining on-demand with cellular

Hybrid monitoring approaches offload parts of the communication through unused bandwidth of different wireless communication technologies in local on-demand networks to reduce the load on the cellular infrastructure. Offloading describes the combined usage of cellular infrastructure-based and wireless (on-demand) communication, such as in MANETs or Wi-Fi assisted networks, according to [147] (see Section 2.4). It is realized by a selected subset of clients acting as gateways or cluster heads [155].

JANUS [164] is a hybrid approach for wireless networks. The authors use Pastry [166], a distributed hash table, to allow for the availability of the monitoring information on all clients in the mesh network. JANUS can measure required information from some layers of the stack. However, the authors do not consider the information measurement on all layers in their approach.

Antler [143] is a hybrid multi-tiered approach for metric collection in wireless networks. A central entity retrieves the required information from the APs in the network, which again collect the data from the clients in the wireless network. Antler aims to diagnose a problem or fault at the lowest tier of the hierarchy with the minimum required level of detail. Higher tiers are used to collect more data if a diagnosis cannot

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[1] https://www.sevone.com/solutions/4g-lte-wireless-network-monitoring

[2] https://www.qosmotec.com/products/mobile-network-tester/

be made at a specific tier. Raghavendra et al. [143] stress "the need for a dynamic and adaptive metric collection system" in their work. However, challenges such as the influence of mobility and unreliable wireless connectivity remain unconsidered.

Guerilla by Shen et al. [175] is a hierarchical monitoring and management system. The approach by Shen et al. relies on a central network manager, which receives incoming information from cluster heads in the network. Cluster heads further collect information from their neighbors. The central manager creates network policies based on the incoming information and transmits those network policies back to the cluster heads. Network policies are only available for clients that are directly under the coverage of a cluster head as the approach does not use multi-hop distribution techniques for the local wireless network. The authors allow for flexibility and continuity of the monitoring process by enabling its cluster heads to make their own adaptation decisions. Furthermore, clients that have processing capabilities are not limited to polling during the information collection process. The authors of Guerilla stress the need for self-management of the clients in an adaptive and distributed manner but lack details on the realization. Shen et al. [175] miss the implementation and evaluation of Guerilla, thus the effects on network bandwidth utilization are unclear.

Relying on hierarchies with gateways

Al-Radaideh et al. [141] propose a structural health monitoring system for highway bridges in their work. The authors propose a system in which bridges are equipped with a wireless sensor network and a master coordinator, which acts as a gateway. The master coordinator collects the information locally from the sensors and uploads them to a cloud-based server. In the presented approach, the sensors are not moving. Thus, the applicability of the approach for the mobile domain is limited as additional effects as partitioning and short-termed connections are not considered in [141].

In our earlier work [162], we propose a hierarchical monitoring system that relies on a gateway to cloud communication. Gateways are determined using a static approach and advertise their presence in the network. Non-gateway clients overhearing those advertisements, connect to the *best* gateway using a multi-hop, contention-based forwarding scheme [103, 212]. Due to the static gateway selection, the applicability for highly dynamic and heterogeneous mobile scenarios is limited.

3.1.3 *Decentralized Strategies*

Decentralized monitoring approaches are organized in flat or hierarchical structures. The approaches use on-demand wireless communication, such as MANETs or DTNs. In hierarchical, decentralized approaches the mobile clients are assigned different roles, which are determined with gateway selection and clustering solutions as detailed in Section 2.4.

Flat & hierarchical structures

Ramachandran et al. present DAMON [144], a two-tiered decentralized monitoring approach, which relies on an agent-gateway topology for the collection of relevant information. A controlled flooding approach is used to send data from mobile agents to sinks. The authors assume non-mobile and pre-defined gateways of the network operator's choice.

Mesh-Mon by Nanda and Kotz [132] utilize a similar two-tiered approach as Ramachandran in [144]. The authors consider a detailed local and a sparse global network view to gain precise monitoring results if needed. Gateways monitor their k-hop neighborhood to construct a detailed local view of the network. By sharing local views among the gateways, a sparse global view is maintained. The authors assume the existence of static and mobile clients in the approach. In the small-scale evaluation with 25 clients, heterogeneity of the clients is not considered.

Scalable but less control

Battat et al. [14] use a three-tiered approach called HMAN. The affiliation to a tier is based on weights of the clients, which incorporate weighting factors such as the used routing protocol, the distance to other clients, and the resources left on the client. HMAN relies on a given routing protocol for the transmission of the monitoring information. The approach does not separate data and monitoring communication. Thus, service interruptions of the core network management service are likely.

Riggio et al. [163] propose a two-tiered distributed monitoring approach with OBELIX. The tiers are established by assigning the following logical roles to the clients in the network: taps and sinks. The logical roles determine the monitoring functionality the respective clients perform. Taps, also referred to as monitoring agents, retrieve the needed information either by passive traffic flow observation or by active on-demand / periodic measurements. Sinks are the management entities used for analysis and maintenance of the global view of the network state. In the bootstrap phase of OBELIX, taps select a set of sinks used to report the collected information. One of the sinks is seen as the master sink for a tap, while the other sinks are used if the master sink fails. During operation of OBELIX taps are always associated to at least one sink. While the approach by Riggio et al. considers "adaptivity, robustness and efficiency requirements" in the design, the influence of client mobility is not further considered.

Bio-inspired approaches

BlockTree by Stingl et al. [188] describes a hierarchical decentralized monitoring approach for location-based services. The authors rely on the division of the observed area into blocks of smaller and larger size on different tiers. BlockTree uses location-awareness in the monitoring process to provide detailed information of neighboring blocks and a sparse summarized view on higher tiers. The approach benefits from dense populations and shows weaknesses in sparsely populated areas as the created hierarchy needs frequent updates of the relations between the clients.

Mobi-G [190] is a flat, decentralized monitoring approach. The approach relies on gossiping of the monitoring information between the clients. Due to the flat topology of the approach, it can achieve good performance in less densely populated areas compared to hierarchical approaches. Both, BlockTree and Mobi-G, require detailed information about the clients' location as discussed in [187], which may render the approaches less useful in scenarios where localization techniques are not reliable or in worst case are not available at all.

Tuncay et al. [197] try to reduce the total number of measurements performed within an area of relevance. Based on the selection of a subset of appropriate clients for monitoring an overview of the whole area should be constructed. The authors rely on a-priori knowledge of the network obtained by so-called recruiting clients, which select the clients to perform the monitoring task. In dynamic and heterogeneous networks where mobility patterns and interconnections of clients do change over time and are not known in advance, a-priori knowledge is not available or costly to gather, rendering the approach unsuitable.

3.1.4 *Position Estimation for Location-based Services*

According to Basagni et al. [12] mobility, i. e. the frequent change of the location of a user in the network, is a main influential factor and challenge for communication mechanisms and applications. The estimation of user positions is essential in today's mobile networking scenarios and not only relevant for location-based services. Mechanisms for location retrieval in mobile wireless scenarios mainly rely on fingerprinting, geometric estimations [82] such as triangulation, or local sharing of positions between clients that have access to accurate positions and those that do not [113, 181].

Localization methods

The authors of LOCALE [205] and Kampis et al. [93] focus on location estimation in sparsely populated networks with non-mobile clients. The estimations are based on frequent position readings of the neighbors that are again used for prediction of the own position. These approaches share the requirement that all clients do have access to localization techniques to provide accurate location estimation results.

Li et al. [113] propose a collaborative location estimation approach. The authors rely on so-called multidimensional scaling and maximum-likelihood estimation. The main objective of the approach is on accurate location retrieval for non-mobile environments with densely interconnected clients in a grid structure. Due to user mobility, the density and the structure of the network are subject to change. The usage of mobile anchor clients equipped with Global Positioning System (GPS) that frequently broadcast their location information to other (non-mobile) clients is proposed in [181].

In [82] Hu et al. propose location estimation using the Monte Carlo localization method. The approach needs local communication among clients to achieve the localization and assumes availability of neighborhood information.

Indoor localization

The authors of [27] propose an approach for indoor localization in urban areas. The approach targets the localization of individuals in indoor environments, where it is likely that clusters of humans can block a Wi-Fi signal. Chan et al. [27] rely on clients that have a higher confidence of accuracy in their location estimation to help to fine-tune location estimations of neighbor clients that have a lower confidence. Three steps are performed to achieve this goal. In the first two steps, adjacent neighbors are detected by the individual clients and the location measurements are rated considering their accuracy. In the third step, a collaborative approach is used to reduce the target client's estimation error with location information of the neighboring clients. However, the authors assume a maximum distance of 0.5 m between clients in the formed clusters. The authors of [27] assume a a-priori known and configured setting with the presence of static anchor clients that are used to re-calibrate potential positioning errors.

Reference points for re-calibration

Both, Chan et al. [27] and Li et al. [113] use reference points that have knowledge about their exact position in the localization process. The approaches discussed above do not focus on the per-client or overall overhead and the introduced cost of the location retrieval process.

Doherty et al. [56] use information on the connectivity and pairwise angles between clients for the location estimation. The authors propose a method for the estimation of unknown positions of clients by placing rectangular bounds around the possible positions. Doherty et al. assume non-mobile clients in their work in combination with error-free sensor readings and a-priori knowledge of the network characteristics.

Sensor errors and mobility influence

Ott et al. [136] discuss the influence of location errors in the estimation process on the performance of location-based services on the example of geo-based content sharing. The results indicate that networks with dense populations are relatively robust to sensor errors. However, with less controllable redundancy or when not every client is required or able to perform location estimations, e. g., to save resources, sensor errors gain in relevance. The authors stress the point that unrealistic mobility models such as the random waypoint [89] or the gaussian movement model [115], exhibit stronger dependency to sensing errors, as less frequent encounters are likely compared to mobility models that incorporate realistic social ties between users. According to Ott et al. [136] the impact of a sensor error is depending on the application using the location estimation as well as on the location estimation approach.

3.2 OFFLOADING THROUGH GATEWAY SELECTION AND CLUSTERING

In the following we discuss offloading approaches in mobile networks, for which we split the detailed discussion into gateway selection and clustering strategies. Increasing dynamics and load requirements in mobile networks reinforce the need for offloading of data through the unused bandwidth of complementary wireless technologies [147]. Offloading approaches that utilize the combination of cellular infrastructure-based communication and wireless (on-demand) communication, such as in MANETs or Wi-Fi assisted networks are discussed in the following. Afterwards, we discuss gateway selection and clustering approaches. Both gateway selection and clustering are relevant for the assignment of roles within offloading.

Kemp et al. [100] propose the offloading of computational tasks as resource saving method for a monitoring system. The approach shows potential savings by offloading of computational tasks but depends on the cellular connectivity of the clients.

Bao et al. [10] propose the usage of clustered clients to reduce the load on the cellular network. The system shows the benefit of device-to-device offloading from gateway clients but lacks the use of public APs. Lou et al. [118] describe how neighbors with better connectivity characteristics might be used to maximize the per-client throughput in a network. In [209] the authors use a shared notification channel to save resources on the clients.

Graubner et al. [72] show the usability of role assignment in a centrally controlled topology management system for Software-defined Wireless Networks (SDWNs). In DROiD Rebecchi et al. [146] follow the idea to reduce the usage of infrastructure-assisted communication to a maximum. DROiD initially injects (popular) content to a few clients in the network. The content is distributed by opportunistic propagation in a local on-demand network. Each client receiving the content acknowledges its reception to the central entity. After further re-injections and more spreading of the content locally, DROiD can guarantee complete coverage of the targeted clients.

Luo et al. [118] focus on the throughput achieved on the individual clients in the network by utilizing adjacent gateways to obtain the needed information in case the own connectivity characteristics are not sufficient. The authors of [85] aim to improve the coverage and scalability applications achieve through offloading. The authors assume that content is shared opportunistically among users when they meet. Izumikawa et al. [86] achieve a robust offloading by utilizing a store-carry-forward routing mechanism. This method is used to carry delay tolerant data from congested areas, in which the infrastructure faces high load, to areas where the infrastructure is not congested. Due to its characteristics, this approach is suitable for data that does not imply latency requirements.

Fairness in offloading

Li et al. [114] observe fairness characteristics of the offloading process concerning the traffic that is downloaded by clients. The authors present an approach that uses opportunistic and connected device-to-device communication strategies. With connected ad hoc communication, the authors refer to a connected path from an infrastructure-based cellular station to a client using at least one intermediate hop in the local network. Data is then sent using this established path to the respective client. To overcome mobility, which increases the possibility of a breakdown of the connected paths the authors use an opportunistic store-carry-and-forwarding approach to reach the intended receiver.

3.2.1 *Gateway Selection Strategies*

Specific utility functions

Similarities of the offloading approaches proposed in the research community are that they rely on mechanisms for *i)* the selection of gateways and *ii)* the assignment of clusters of remaining clients to a gateway. Existing gateway selection approaches use either a deterministic or stochastic procedure according to Chinara et al. [33] and Bentaleb et al. [18]. In the following, we organize the discussion of the gateway selection strategies based on the proposed utility function.

Basic strategies select the gateways according to IDs or neighborhood relationships, such as the outer degree of connections. The lowest ID approach [8] and the linked cluster algorithm [59] aim to select a gateway without a central coordinator. Both assume that all entities in the network have unique IDs. By exchanging information on the own ID and the IDs of adjacent clients in the network, clients can locally determine which role they take. With the ID being the only criteria for the selection of gateways, some clients perform the gateway role more frequently resulting in an unfair utilization of the resources in the network. The *least cluster change* approach by Chiang et al. [32] tries to reduce the frequency with which gateways and respective clusters are determined to reduce the overhead. The approach by Gerla and Tsai [69] aims to provide connectivity in a mobile network by selecting gateways in clusters in a way that they have a high connection degree to clients from adjacent clusters. The approach differentiates between *i)* gateways, *ii)* clients that have a connection to a gateway, and *iii)* uncovered clients. Uncovered clients become a gateway once there is no client in their one hop neighborhood having a higher connection degree.

Energy efficiency

Energy efficiency is another objective, which is highly relevant concerning the resource-constrained nature of mobile clients. The Low-Energy Adaptive Clustering Hierarchy (LEACH) by Heinzelmann [78] realizes a distributed optimization approach. The authors aim to distribute the energy consumption among the clients in the network to maximize the network lifetime. In a per-round comparison of a calculated threshold $T_r(i)$ with a drawn random value each client c_i decides if it becomes a gateway. The threshold is calculated as shown in Equation 1:

$$T_r(c_i) = \begin{cases} \frac{p}{1-p\cdot(r \mod \frac{1}{p})}, & \text{if } c_i \in G \\ 0, & \text{else.} \end{cases} \tag{1}$$

The ratio of gateways is denoted with $p \in [0, 1]$. r represents the number of successive rounds a mobile client has not been a gateway since the last time being a gateway. The set G consists of all clients that have not been a gateway in the last $1/p$ rounds. The gateway ratio p is described as the ratio between the number of gateways k and mobile clients n which results in $p = k/n$. Being a gateway for a long time reduces the possibility to become a gateway in one of the following rounds. The authors assume homogeneous sensors considering their resources and communication technologies. The ratio of gateways p must be set before running LEACH.

The authors of [77] propose a centralized version of LEACH. A deterministic approach, based on simulated annealing [198], is used to determine an optimal number of clusters. The goal of the approach is the reduction of the energy consumption between the gateway and non-gateway clients. In the Stable Election Protocol proposed by Smaragdakis et al. [179] energy heterogeneity of the clients is considered in the gateway selection process. The approach aims at extending the time until the first client runs out of battery to a maximum, assuming that the network stability decreases significantly after the first clients run out of battery. The clients in [179] are assumed to be quasi static, thus mobility influences on the gateway selection process are reduced. Ali et al. [1] follow the same goal as [179].

Similar to the approach before, Qing et al. [140] assume quasi static clients in their proposed selection strategy DEEC. The approach selects gateways using a probabilistic value based on the ratio of the energy of each client and the average energy in the network. In DEEC the time a client is acting as a cluster head depends on its initial and residual energy [140]. The authors present two methods. The first considers the initial amount of energy as well as the current energy level. In the second method only considers the current energy level. DEEC cannot guarantee for a fixed number of gateways due to its stochastic nature. Furthermore, as the selection is based on stochastic values and is only considering the energy level, the result of DEEC and the approaches above is not location-aware. In the worst case, all selected gateways are in direct proximity to each other.

MOBIC by Basu et al. [13] and MobiHD by Konstantopoulos et al. [107] focus on the stability of the gateway selection process in mobile networks. The authors of [13] aim at selecting those clients with the lowest mobility as gateways to provide for stability in the selection process and assignment of non-gateway clients to the former. For the calculation of the mobility, the authors rely on the relative movement speed between the stations [13]. Konstantopoulos et al. [107] present MobiHD, a predictive and decentralized approach. The gateway selection within this approach is based on the prediction of the stability of the neighborhood relations of each client. The client with the highest stability in a cluster is selected as gateway. The prediction used by the authors is based on the observation of the neighborhood of the mobile clients over time, which is understood as a stream. This stream is analyzed for entropies to find those neighborhoods that occur more often and occur very likely in future. Thus, candidates for being gateway are the clients that have a high degree of neighbors and where the possibility that those relationships will remain is high. Both MOBIC [13] and MobiHD [107] require more computational resources than other approaches and may take too long for direct processing on the clients.

Mobility awareness

Many gateway selection approaches combine multiple values to allow for the consideration of more than one relevant factor. The approach by Chatterjee et al. [28] considers the number of neighbors, the achieved signal range, the location, mobility and the energy level of the clients. The authors establish a hierarchy in which gateways are assumed to handle the data of a predefined number of non-gateways. From a candidate list of all clients, those with the lowest weight are selected as gateways and removed from the candidate list. Clients in the neighborhood of the selected gateways are assigned to the former. This process is repeated until the candidate list is empty.

Weighted metrics

The approach by Hussein et al. [84] uses the spreading degree, neighborhood connectivity, energy consumption and the average velocity of the clients as input for the weighted computation. For more details on the spreading degree and the neighborhood connectivity, we refer to [84]. Whenever the energy level of a gateway falls below a given threshold or a mobile station is not covered by a cluster anymore, the selection process is triggered. The approach lacks the normalization of all input weights; thus, some factors may have a stronger influence than intended. More approaches utilize a weighted metric approach to achieve the selection of gateways and the assignment of clients to the gateways such as CEMCA by Tolba et al. [195] and BEC-LEACH [48].

3.2.2 *Clustering Strategies*

For clustering we consider three main categories as introduced in Section 2.4: *i)* density, *ii)* partition, and *iii)* hierarchy. As some of the gateway selection approaches discussed above are already clustering the clients when assigning them to a gateway, we focus on distinct clustering algorithms in the following. In the domain of density-based clustering Density-Based Spatial Clustering of Applications with Noise (DBScan) [62] is well known. The approach clusters points based on the density in an area while representing those points that are not in a group of clients individually. Approaches that propose minor improvements for DBScan emerged in recent years [81, 203].

K-Means++ Clustering (k-Means++) is a partitioning clustering approach by Arthur and Vassilvitskii [4], which is based on k-Means [87]. Partition-based clustering approaches use a predefined number k stating the intended number of clusters. The clients are switched in between the clusters until a local optimum is found for a given approach specific criteria. The hierarchical clustering approach DIANA by Kaufman and Rousseeuw [96] starts the clustering process with one cluster containing all clients. Successive clients with the highest inequality are removed from the cluster and form a new one. Clients that have a shorter distance to the new cluster are re-assigned to the new cluster. Combinations of the main categories are also possible, as de Berg et al. show in [47] by combining grid- and density-based approaches.

3.3 TRANSITION-ENABLED COMMUNICATION MECHANISMS

Transitions in the field of . . .

Network dynamics and heterogeneity increase the need of adaptive communication systems and mechanisms. Flexible systems that allow *i)* the handling of the increasing dynamics in current and future networking scenarios and *ii)* to overcome the side effects of solutions that provide flexibility by losing required unique features have been proposed in recent years. Transitions between mechanisms, as described in [66, 67, 148, 200], proofed their benefit by overcoming the challenges mentioned above.

. . . video streaming.

Within the domain of video streaming the works by Rückert, Wichtlhuber, Stohr and Wilk [167, 199] have been proposed. TRANSIT, by Wichtlhuber et al. [199], supports transitions between different peer-to-peer live streaming mechanisms. The proposed approach overcomes the limitations of current peer-to-peer live video streaming mechanisms, which perform well under certain conditions. In large-scale events, where environmental conditions are very likely to change in a short period of time, TRANSIT can provide for high performance as the mechanisms for topology management and scheduling can be exchanged seamlessly. The approach shows good resilience in flash-crowd scenarios and that user-centric performance indicators as startup delay and playback smoothness are nearly unaffected under massive churn. TRANSIT introduces, compared to non-adaptive solutions, a comparably low overhead. Rückert et al. [167] analyze the influence of the utilized streaming topology during flash crowd events on the achieved performance. Different topological optimizations lead to an improved QoE at the cost of a slight increase in the startup delay. Wilk and Richerzhagen [152, 201] show the utilization of a transition between unicast and broadcast video delivery.

. . . topology control.

In wireless (ad hoc) networks the used network topology has a significant influence on the resulting communication characteristics. Kluge et al. [104, 105] focus on topology control algorithms and transitions between communication topologies in the network. A transition between topologies is achieved by the removal or addition of edges in the used connectivity graph. In [184] Stein et al. propose a model for topology adaptation based on rule language. The authors show the usability of the approach and its ability to express a large fraction of related topology adaptation algorithms.

. . . publish/ subscribe.

The author of [148] proposes the utilization of transitions in the domain of publish/-subscribe. The author shows that transitions between mechanisms for location-based filtering and locality-aware dissemination of events improve the usage of locality in the communication and thus the achieved performance of publish/subscribe mechanisms. The system BYPASS [150] includes an encapsulation method for filter schemes and a scheme-specific context update protocol. The system introduces intra-proxy state transfer, as presented in Section 2.5, to allow for seamless transitions on single proxies. BYPASS relies on the centralized coordination of transitions using direct one-hop connections to distribute the transition decision in the network.

Luthra et al. [119] propose transitions in between operator placement mechanisms in a complex event processing system with TCEP. The authors enable the seamless exchange of distinct operator placement mechanisms at runtime through transitions, proposing a cost-efficient and a lightweight learning algorithm. Two transitions execution strategies are supported within [119]: a moving fine-grained state sequential transition and a seamless minimal state concurrent transition. Both strategies differ in the number of operator migrations they allow at the same time. Similar to our contribution in the area of adaptive offloading, presented in Chapter 4, the authors stress the relevance of placement in their research domain. In our work, we consider both centralized and decentralized role assignment approaches and bring those in a transition-enabled mechanism together. Our approach is not limited to the domain of role assignment and offloading in wireless (on-demand) networks.

. . . complex event processing.

Hark et al. [75] detail the usage of different loss estimation techniques in a Software-defined Network (SDN). The authors motivate the exchange of different loss estimation techniques under varying conditions. However, the authors lack the design and implementation details on the execution of transitions and, thus, do not analyze how a transition affects the performance of the system in the domain of SDN. Resilience as the "ability of a system to provide and maintain an acceptable level of service in the face of faults and challenges to normal operation" [186] is important [169] considering network management. The usability of resilience management has been shown in different network domains such as SDN [178] and cloud computing [177]. We are not explicitly addressing the resilience strategy loops in this work but argue that transitions can be used as a mean to improve the resilience of a communication system and network. Furthermore, monitoring a network is a core part of the background loop of resilient systems [186] and must thus, provide for the needed information under a variety of challenging environments.

. . . software-defined networks.

3.4 SUMMARY

Monitoring and offloading approaches exist for specific network and environmental conditions. Most of them assume that the needed information is already available on the clients or the entities performing the computations. However, the measurement and the retrieval of information in the highly dynamic environment of mobile (on-demand) networks is a challenging task. Obtaining information locally on the clients across the layers of the communication stack is necessary. Additionally, a sensible selection of the data that should be measured must be considered with respect to the introduced overhead as the amount of the collected data must be reduced to the necessary [143]. To guarantee the seamless operation of the monitoring process, a separation of the monitoring and application traffic in the network is desired.

In mobile networks, the location of users gains in importance as it determines to a large extent the prevailing networking conditions. Within the domain of location-based services the retrieval of the position of users lacks a joint consideration of *i)* position accuracy, *ii)* cost, and *iii)* fairness considering the resources of the mobile clients. Furthermore, accurate location information is mostly assumed to be available on all clients. To handle the increasing dynamics monitoring as well as offloading approaches must inherit adaptivity [175].

Offloading is a frequently used approach to reduce the load on infrastructure entities or to handle dynamics in the network. However, offloading mechanisms themselves use fixed configuration setups to select gateways and to establish clusters. In changing environments, the lack of adaptability influences the resulting performance significantly. Our first contribution AssignMe.KOM describes an offloading service that is able to integrate a multitude of offloading approaches, while additionally allowing for transitions between multiple configurations. The transition-enabled role assignment service allows for constant high performance of the offloading process as the system is able to adapt to changing requirements and conditions using transitions. Furthermore, centralized and decentralized gateway selection and clustering algorithms are incorporated into AssignMe.KOM, allowing for unprecedented comparability among different approaches.

In the design and analysis of our second contribution, the transition-enabled monitoring service AdaptMon.KOM, we consider the research gaps identified in this section. We allow for cross-layered and protocol independent measurement of information in the monitoring service. The monitoring service can realize monitoring functionality of a wide range of existing monitoring solutions by using transitions. Besides, we introduce additional transition execution and decision spreading methods to handle the dynamics of the network and environment. In a case study, we focus on the collaborative monitoring for location-based services.

4

ASSIGNME.KOM: ENABLING ADAPTIVE OFFLOADING

In the analysis of the related work of monitoring approaches in Section 3.1 we identified the communication patterns as the distinctive characteristic of network monitoring approaches. For many communication patterns used in decentralized and hybrid monitoring approaches the selection and clustering of clients is essential to, e. g., establish hierarchies among clients. Thus, as explained in Section 2.4, selection and clustering techniques as used in offloading approaches are also needed within AdaptMon.KOM. Concerning the dynamics of mobile networks, we identified the gap of adaptability in today's offloading approaches in Section 3.2. Beside the usage of offloading techniques within AdaptMon.KOM, offloading is used by many mechanisms to handle dynamics in mobile networks [147, 208]. As discussed in Section 3.2, current offloading approaches are limited in their applicable range and are mostly tuned towards a specific utility function, such as maximal offloading gain or cost reduction. However, conditions in mobile networks and application requirements change over time. The observable dynamics lead to a possible degradation of the selection and clustering results obtained by the offloading mechanism. This deterioration of the results is then passed into mechanisms that utilize the offloading results.

Adaptive centralized & decentralized offloading

To this end, we designed AssignMe.KOM [158, 161] as a service to support the integration of a multitude of offloading solutions, similar to those presented in Section 3.2, while allowing for transitions to handle the dynamics of network conditions and application requirements. Within AssignMe.KOM we rely on the specialized selection and clustering approaches presented in Section 3.2. By enabling transitions within AssignMe.KOM, the service is able to adapt to dynamics in the network and changing requirements. It enables the usage of both centralized and decentralized offloading approaches by encapsulating the main functionalities of the former into a generic framework. AssignMe.KOM allows for better comparability of selection and clustering approaches.

4.1 CONCEPTUAL OVERVIEW

The goal of AssignMe.KOM is *i)* to allow for the handling of dynamics in the network and the application requirements within offloading and *ii)* to map the process of client selection and clustering to utility functions depending on the current need. To achieve this goal, we designed AssignMe.KOM as a service that allows for centralized and decentralized assignment of roles in the mobile network. The main parts of the design are detailed in Section 4.2, including the encapsulation of the main functionalities of offloading approaches to allow for an adaptive usage in dynamic environments. The role assignment is the basis for any offloading application as introduced in Section 2.4. To allow for transitions between different selection and clustering approaches we

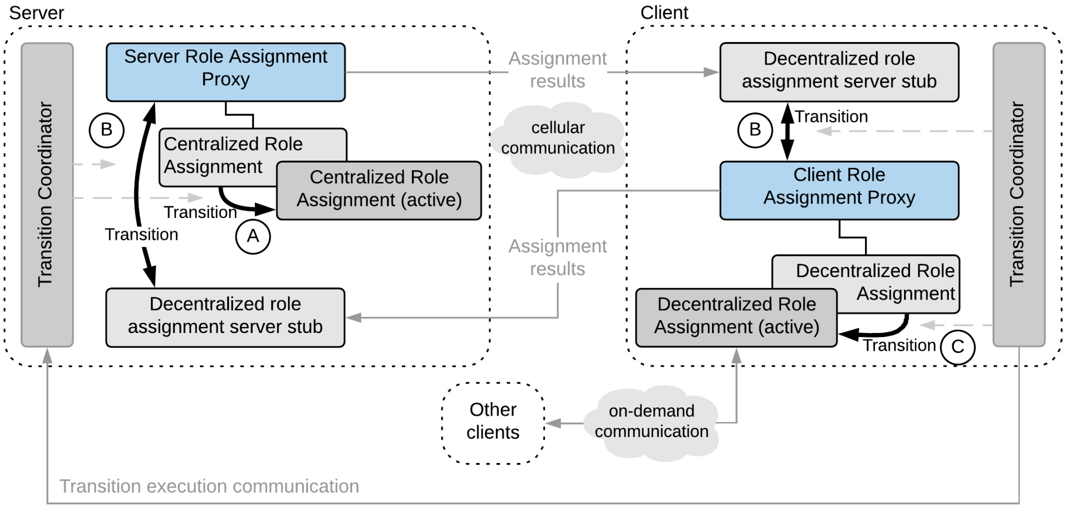


Figure 10: Client- and server-side components of AssignMe.KOM as proposed in [158].

identified six main classes of selection approaches in [161]. We explain these classes in Section 4.3. In Section 4.4 we detail current mechanisms relying on the functionalities provided by AssignMe.KOM, proving the general usability of the service. To improve readability, we refer to clients selected by the role assignment procedure as gateways in the following.

4.2 ENCAPSULATION OF CENTRALIZED AND DECENTRALIZED ROLE ASSIGNMENT

The structure of AssignMe.KOM as presented in [158, 161] allows for centralized and decentralized role assignment. AssignMe.KOM consists of components for *i)* coordination of the centralized or decentralized assignment of roles, *ii)* for the specific mapping of the selection and clustering approaches used within the service, and *iii)* for communication of the assignment results in between mobile clients and with the central components. Figure 10 shows the client- and server-side components of AssignMe.KOM. We rely on a proxy-based architecture, similar as in AdaptMon.KOM (see Chapter 5) and other transition-enabled mechanisms [148, 199], to allow for transitions between centralized and decentralized role assignment strategies. This architecture is two tiered. When configured as a centralized approach, we allow for transitions between centralized role assignment strategies, e. g., different client selection approaches, within the centralized role assignment proxy. This is annotated with *A* in Figure 10. The assignment process of both the centralized and decentralized approach is detailed in Section 4.3. There, we also detail how our contribution allows for comparison of the selection and clustering strategies proposed in the research community so far.

Transitions between centralized & decentralized offloading

For transitions between centralized and decentralized role assignments we rely on the proxies and stubs on both sides. The process is detailed with the aid of Figure 10, in which we illustrate an exemplary transition from centralized to decentralized offloading with annotation *B*. A running assignment strategy is not needed on the central proxy after the transition. Therefore, on the server side the usage changes to the stub that is needed to receive assignment results. The client is not required to do any additional actions before the transition, as no selection or clustering is done locally. Before the transition, clients use the client stubs as no local processing is required. After the transition, the client role assignment proxy is used with a decentralized strategy. For the transition between centralized and decentralized role assignment the following transition plan (as introduced in Section 2.5) is executed:

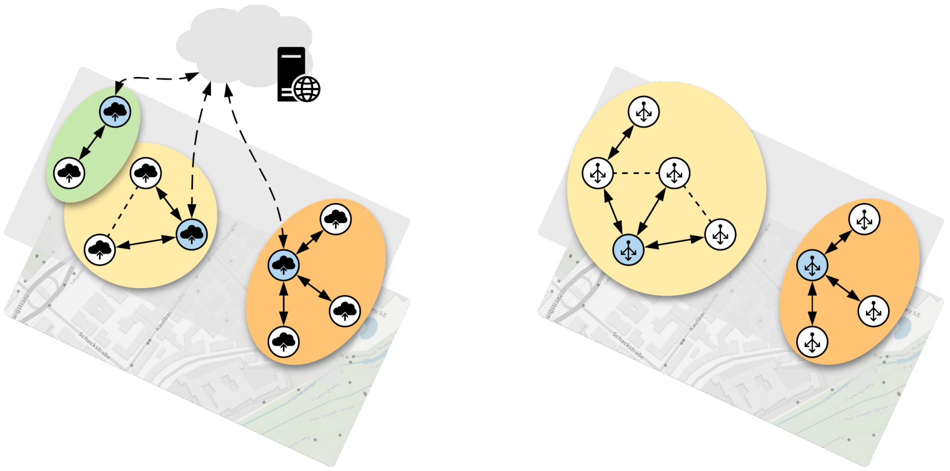
$$\begin{aligned} 1^{\text{st}}\text{ Server Role Assignment Proxy:} \quad & \mathrm{T}^{\forall}_{\text{central}} : \mathrm{M}_{\varnothing} \rightarrow \varnothing \\ 2^{\text{nd}}\text{ Client Role Assignment Proxy:} \quad & \mathrm{T}^{\forall}_{\text{client}} : \varnothing \rightarrow \mathrm{M}_{\varnothing} \end{aligned}$$

Stubs are used for receiving the assignment results. With the centralized role assignment, the obtained selection and clustering results might be required by mechanisms running on the clients. For this purpose, this information can be shared using the stubs. The coordination of transitions is decoupled from the mechanism. For transitions between decentralized role assignments only the client proxies are involved as illustrated with annotation *C* in Figure 10. The coordination of transitions within AssignMe.KOM relies, similar to AdaptMon.KOM, on proxies and transition coordinators on server- and client-side. We explain these in detail in Section 5.3 after introducing additional concepts such as transition decision spreading within transition-enabled mechanisms.

Assignment result distribution

AssignMe.KOM is triggered by applications or mechanisms using offloading. Depending on the current configuration and used selection and clustering approaches additional information is needed. We obtain this information in the centralized configuration relying on a monitoring service, such as AdaptMon.KOM. After the required information is obtained from the respective clients in the network the active centralized role assignment starts computation on the server. This results in a set of selected gateways with assigned clients to each gateway forming a cluster. The result is either *i)* returned to the requesting mechanism if it notifies the clients itself, *ii)* distributed to all affected clients to allow for a higher information basis in the mobile network, or *iii)* only sent to current and previous gateways (i. e., only affected clients). In the third case, where only current and previous gateways are notified, we omit the clustering information as it is not required for some application scenarios [148, 149]. The centralized role assignment has multiple configurations in which the execution of the gateway selection and clustering can be changed. In combination with deterministic and stochastic selection approaches six main classes for the categorization of the strategies of the related work result. We detail these classes in Section 4.3.

In dynamic networks the use of centralized strategies for role assignment might not be feasible or intended due to overhead or reliability reasons. In such cases and in case of mobile networks without infrastructure support, a distributed, decentralized role assignment solution is needed. The decentralized role assignment part of AssignMe.KOM solely relies on ad hoc communication between the mobile clients to determine gateways and to subsequently cluster the remaining clients. We identified, based on the analysis of the related work in Section 3.2, four phases that are needed to achieve this goal and introduce them in the following. The concept of centralized and decentralized selection of gateways and clusters is illustrated in Figure 11. Se-



(a) Centralized gateway selection and clustering (b) Decentralized gateway selection and clustering

Figure 11: Visualization of the centralized and decentralized selection of gateways and clusters. Gateways are highlighted in light blue.

lected gateways, in light blue, and clusters are either calculated by a central entity in the case of the centralized configuration of AssignMe.KOM (see Figure 11a) or in a collaborative fashion by the clients in the network (see Figure 11b).

4.3 INCORPORATING GATEWAY SELECTION AND CLUSTERING STRATEGIES

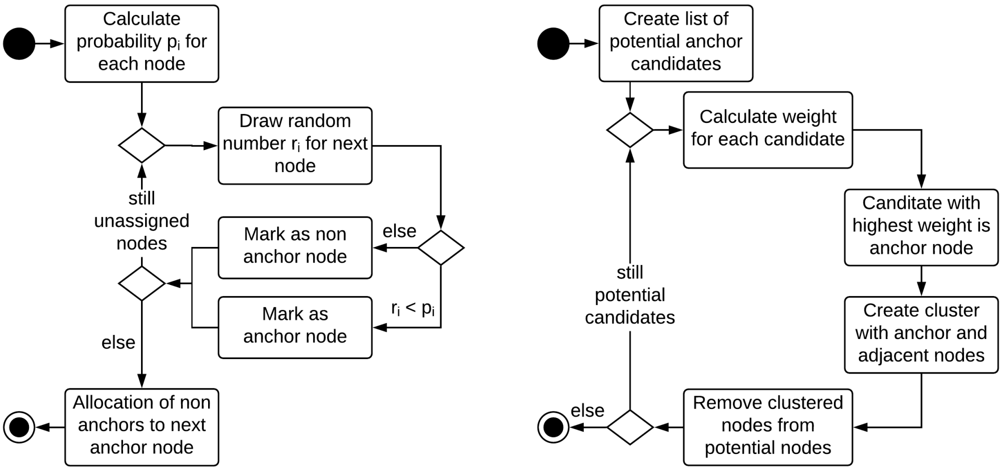
Six centralized classes

We detail the integration of gateway selection and clustering strategies for both the centralized and decentralized role assignment within AssignMe.KOM in the following. As selection and clustering are functionally not mutually dependent, we can change the execution order of both. In combination with deterministic and stochastic gateway selection approaches such as [1, 28, 78] this results in six main classes [158, 161], which we will explain in the following.

For the assignment of roles, i. e., selecting gateways and clustering of clients, exact algorithms may not be a feasible solution. The assignment of n clients into k clusters is a combinatorial problem of the type of Stirling numbers of the second kind [71], thus one would have to solve the problem shown in Equation 2:

$$S_n^{(k)} = S_{n,k} = \frac{1}{k!} \cdot \sum_{i=0}^{k} (-1)^{k-i} \cdot \binom{k}{i} \cdot i^n \,. \tag{2}$$

For a small network size of 100 clients and 10 clusters this already results in over $2.75 \cdot 10^{93}$ combinations. Solving that problem in networks of larger size in a limited amount of time cannot be guaranteed. Clustering with an objective function, i. e., enumerating all possible ways of dividing data points into clusters and evaluating the goodness of each potential set of clusters by using a given objective function is a



(a) SEC (b) D1C

Figure 12: Process visualization of the stochastic (SEC) and deterministic (D1C) assignment classes used within AssignMe.KOM.

NP-hard problem [121]. Thus, we use heuristic approaches as presented in the related work in Section 3.2 to solve the assignment problem in a reasonable time window.

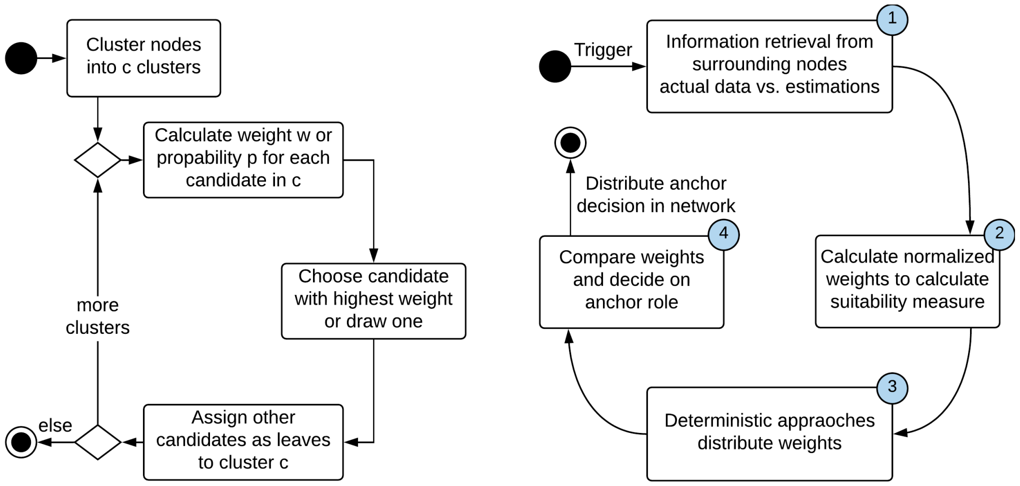
Centralized Role Assignment

Stochastic & …

SEC represents the first stochastic role assignment class. SEC stands for **s**tochastic gateway selection with the number of gateways following an **e**xpectation value and successive **c**lustering of non-gateway clients to the chosen gateways. We show the process of SEC in Figure 12a. The design of SEC is motivated by ALEACH proposed by Ali et al. [1]. In the first step, each client is assigned a probability p_i, which is calculated using a given valuation method. Next, we draw a random number r_i for each client. We mark the client i as gateway if r_i is smaller than the assigned probability p_i, i.e., $r_i < p_i$. The clustering in SEC is done with a best-fit algorithm. This results in clients being assigned to the gateway with the shortest euclidean distance. Instead of the shortest euclidean distance as deciding factor we can also use the shortest path (hops) or the highest RSSI. The number of clusters within the SEC approach is determined by the distribution of the probabilities. This results, due to the stochastic process, in a random distribution of gateways in the network. Thus, there is a possibility for clients not being covered by a gateway. We currently rely on the well-known stochastic selection approaches LEACH [78], ALEACH [1], and DEEC [140]. However, due to the modularity and distinction in the main classes, AssignMe.KOM can easily be extended with many more selection strategies.

… deterministic gateway selection …

D1C uses a combined weighted metric, instead of relying on probabilistic measures. The process of D1C is shown in Figure 12b. D1C chooses gateways based on **d**eterministic functions **one** after another including the **c**luster formation of non-



(a) CD and CS

(b) Phases of the decentralized role assignment

Figure 13: Process visualization of the strategies CD and CS and the phases of the decentralized role assignment of AssignMe.KOM.

gateway clients per round. The algorithm starts the process by calculating weights for each client in a list of potential gateways. In each round the candidate with the highest weight is chosen as gateway. Each round, a cluster covering the adjacent clients is created around the selected gateway. Each round ends by removing the selected gateway and the clustered clients from the list of potential candidates. If after a round unassigned clients are left in the network, the process continues by calculating weights per candidate again. Currently, the weighted approaches WCA [28] and FWCABP [84] are used in D1C as comparison with a static selection.

. . . followed by clustering.

DkC and SkC are very similar to SEC and D1C. However, both classes take the resulting number of gateways k as input parameter for the selection of gateways and clustering of non-gateway clients. We allow for the upper bound of the resulting gateway clients as this is a functionality that may be required by applications to limit the number of clusters created.

The last two classes perform the clustering first and the gateway selection afterwards. CD and CS describe the **c**lustering followed by choosing a number of gateways either **d**eterministic, or **s**tochastic. The two strategies are illustrated in Figure 13a. In the current version of AssignMe.KOM, CD and CS cluster the clients initially using DBScan [62], k-Means++ [4], or a grid-density based clustering scheme, extending the work by DeBerg et al. [47]. When the clustering process is finished one gateway per cluster is determined. Within CD, the calculation of each gateway per cluster is based on a deterministic weight. CS uses a probabilistic function to select the gateways stochastically.

Clustering followed by gateway selection

Decentralized Role Assignment

In situations, where infrastructure-based communication might not be reliable or possible at all, it is essential to provide for role assignment under the dynamic environment of mobile networks. For this, AssignMe.KOM contains components for decentralized role assignment. Based on the analysis of the related work in Section 3.2, we identified four phases that are needed for the decentralized assignment of roles. We visualize the four phases in Figure 13b and introduce them in the following. The first phase depicts the information collection from surrounding clients. Depending on the approach taken, information is based on actual collected data or on estimations retrieved by, for example, clients eavesdropping their proximity. Obviously, actual collected data may be more accurate, but the collection process involves local communication between clients and, therefore, introduces additional overhead. This is similar to the trade-off between passive and active monitoring as explained in Section 2.3.

Four phases of decentralized assignment

In the second phase, clients calculate either a probability or a weight based on the input from the first phase. Similar to the centralized role assignment, we rely on probabilistic and deterministic solutions as seen in Chapter 3. Most algorithms use a suitability measure to select gateways. This suitability measure is based on the knowledge about the client itself. We refer to both the probability (stochastic) or the weight (deterministic) as weight ω_{own} in the following to ease readability. Within AssignMe.KOM, all weights are normalized to allow for comparison among them in the case of local $T^{\bullet}$ or regional transitions T^{C} of the weight computation schemes.

Weight calculation, distribution & comparison

In the third phase, client weights ω_i are distributed. Clients that receive weights during the third phase store those for later comparison. The third phase is not used in stochastic approaches, as they do not involve any additional sharing of weights.

The comparison of weights is done in the fourth phase. The received weights ω_i or the drawn random values for stochastic approaches are compared with the own weight ω_{own}. A client is marked as gateway if its own weight is greater than all received foreign weights ($\omega_{\text{own}} > \omega_i \ \forall\ i$). Newly selected gateways distribute this decision in the network. Non-gateway clients overhearing that message do cluster to the respective gateways they get notified by. If multiple gateways are overheard in a certain interval, the clients select their gateway either relying on a *first heard* or a *nearest first* strategy. Nearest first uses the hop counter of the disseminated messages as distance measure.

Clustering to gateways

In a potential fifth phase, non-gateways can also try to register with gateways they choose individually. Additionally, the decentralized role assignment has a mechanism to trigger (timer- or event-based) the assignment process. Other mechanisms can subscribe to the trigger component to get notified when the decentralized role assignment starts. We use transition-enabled local dissemination approaches for all on-demand communication between clients within the decentralized role assignment. The dissemination schemes use sequence numbers to prevent the unnecessary sending of duplicate messages. To prioritize newer messages, we use an importance value IV_{m_i} between zero and one. Messages seen for the first time are assigned with $IV_{m_i} = 1$ leading to immediate forwarding. Other messages are sent after a delay that depends on their importance value. Messages are deleted if the Time to Live (TTL) of the message is exceeded. We rely on *i)* a flooding-based, *ii)* a contention-based [162], and *iii)* a probabilistic approach for on-demand local communication. We use the flooding-based approach as a baseline for comparison with the second and third on-demand communication approach. We use a contention time t_{con} in the interval $[t_{con_{min}}; t_{con_{max}}]$ to reduce the message overhead in the contention-based solution. t_{con} is based on client attributes such as the number of neighbors, load, or remaining battery capacity. Consequently, the resulting t_{con} per-client differ from each other. A client that overhears adjacent clients forwarding the same message during t_{con} will discard the message, assuming that clients in its surrounding have received the message already. If no other client sending the message is overheard during t_{con}, the client will send the message. This procedure significantly reduces the introduced overhead but may lead to longer latencies reducing the freshness of the information collected [162]. The third approach we use is of probabilistic nature. This message forwarding probability of the third approach is based on the hops a message has taken from the message's originator. This avoids the loss of information due to early dropping of messages in the proximity of the message originator.

4.4 USAGE OF ADAPTIVE ROLE ASSIGNMENT IN DYNAMIC NETWORKS

Offloading & monitoring

Offloading of network traffic using gateways and clusters is essential for the functionality of monitoring in mobile networks. Especially, decentralized and hybrid monitoring solutions benefit from adaptive role assignment as shown in [157, 161]. Thus, the transition-enabled monitoring service AdaptMon.KOM, as introduced in the following in Chapter 5, relies on the services provided by AssignMe.KOM. Within the hybrid monitoring solution presented in [156, 162], we rely on the gateways retrieved from the assignment of AssignMe.KOM. The selected gateways collect and distribute the monitoring information from and among the clients. This introduced hierarchy improves the reliability of the hybrid approach, while reducing the cellular network overhead. We demonstrate how different selection and clustering approaches influence the achieved reliability and performance factors of the hybrid monitoring approach in [161]. The collaborative monitoring mechanism for location-based services as presented in [153] relies on the functionality of AssignMe.KOM to select the gateway clients and to cluster other clients to the respective selected gateways. The gateway clients perform the location measurement relying on a localization method such as Wi-Fi triangulation or GPS position sensing.

Offloading & publish/subscribe

However, the usage of adaptive role assignment shows benefits compared to current static specialized solutions not only in the domain of network monitoring. In [148, 149] Björn Richerzhagen shows the potential of a meaningful assignment of gateways out of a set of subscribers in a publish/subscribe system. Assigned gateways distribute incoming data to other adjacent and clustered subscribers. Thus, by utilizing and benefiting from locality in most interest subscriptions, only relevant data is transferred in the publish/subscribe system. The usage of the forwarding gateways leads to better utilization of resources in the network and increased fairness characteristics of the publish/subscribe approach [149]. A high offloading ratio of up to 70% in an augmented reality scenario is realized with a negligible communication overhead.

Communication in vehicular networks is highly relevant concerning the development towards fully connected smart cars and autonomous driving. Meuser et al. propose a hybrid model for interest-based communication between vehicles in [123, 125]. The Advanced Driver Assistance Systems deployed onto vehicles enable superior safety and comfort functionalities. However, information retrieved from onboard sensors on the vehicles is not sufficient in most cases, which means that external information is needed. The origin of this information can be environmental sensors or other vehicles. The challenge to overcome here is that the range of on-demand communication means is not suitable for the long-range needs. However, the cost for cellular communication is high and a highly reliable network coverage is needed, which cannot be guaranteed. With their hybrid interest-based communication approach Meuser et al. propose a solution for the required long-range communication to overcome high costs and coverage risks [123, 125]. The hybrid system relies, similar to [149], on the publish/subscribe paradigm and uses gateways to offload cellular traffic onto the local on-demand network. Vehicles specify their interest(s) and the route to their individual destination. This is done by vehicles without knowing the interested receivers. In the proposed ad hoc communication approach vehicles are used as information ferries bringing information towards targeted locations (locations of relevance) in combination with the selected gateways.

Offloading & vehicular networks

In another work, Meuser et al. [124] propose a prediction-based approach to assess the relevance of events without requiring prior route knowledge. In the selection of vehicles, only the gateways that are concerned as the most relevant are used for the dissemination of events. This assignment of roles in combination with the assessment of relevance allows the approach to reduce the introduced traffic significantly, while providing a similar performance of the geocast in terms of distribution quality. Current systems to provide convenience- and safety-related functions to drivers take advantage of geocast-functionalities. Those use subscriptions covering certain areas (e. g., cities) or individual route-based subscriptions, resulting in suboptimal precision in the filtering or introducing significant complexity assuming a-priori knowledge of routes. The relevance determination is modeled with the street network and spatio-temporal characteristics of events.

Offloading is essential to improve flexibility of adaptive and non-adaptive systems. In both cases, our contribution AssignMe.KOM provides the needed flexibility to offloading and role assignment which has not been considered so far. In doing so, the service allows not only for transitions between gateway selection and clustering mechanisms to enhance flexibility, it also enables the adjustable alignment of the system's utility function at runtime.

Offloading to improve flexibility

As discussed in Section 3.1, many communication patterns used in decentralized and hybrid monitoring approaches rely on selection and clustering of clients to establish hierarchies among clients. In the following we introduce our second contribution, the transition-enabled monitoring service AdaptMon.KOM, which relies on the gateway selection and clustering techniques of AssignMe.KOM.

5

ADAPTMON.KOM: TRANSITIONS IN MOBILE NETWORK MONITORING

Monitoring is a core necessity for mobile network management as outlined in Chapter 2. Current mobile network monitoring approaches, as discussed in Chapter 3, are designed for specific use cases and environmental conditions in which they perform superior to a one-size-fits-all solution. However, those approaches lack various characteristics required to allow for seamless and reliable monitoring in dynamic mobile networks with varying use cases and environmental conditions. Those include mechanism independence and adaptability of the monitoring [41, 183].

To this end, we propose the transition-enabled monitoring service AdaptMon.KOM [154–157, 162]. Instead of relying on a one-size-fits-all solution, we benefit from the utilization of specialized solutions and transitions between those to allow for seamless and reliable monitoring in dynamic mobile networks. By separating the monitoring functionality from the mechanisms at hand, AdaptMon.KOM allows for the monitoring independently of the mechanisms currently used. To allow for high flexibility, the monitoring service must, depending on its current configuration, adapt to frequent changes in the environment by changing the roles of the clients. The variable assignment of roles is achieved by relying on AssignMe.KOM as detailed in Chapter 4.

In Section 5.1, we provide the conceptional overview of AdaptMon.KOM. The separation of the monitoring service from the monitored mechanisms is explained in Section 5.2. We detail the identified main functional components for the required mapping of monitoring functionalities in Section 5.3. The transition-enabling components of our proposed monitoring-service are explained in Section 5.4. As example for a highly relevant use case, we detail a collaborative monitoring solution for location-based services in Section 5.5. This combines the concepts of *i)* the transition-enabled monitoring service and *ii)* the adaptive offloading service AssignMe.KOM (see Chapter 4).

5.1 CONCEPTUAL OVERVIEW

The design goal for AdaptMon.KOM is to use the monitoring mechanism that performs best under the current conditions, e. g., regarding network load and dynamics, by exchanging the active monitoring mechanism at runtime and still satisfy the requirements. This enables reliable and accurate monitoring in dynamic mobile networks without losing granularity of the monitoring process due to unsuitable utilization of mechanisms in conditions they are not intended to work under. Consequently, AdaptMon.KOM allows the execution of centralized, decentralized, and hybrid monitoring mechanisms (see Chapter 3) to provide accurate monitoring information under any condition. We enable the dynamic exchange of monitoring approaches using transitions, by mapping main functional components of the monitoring approaches to proxies, as detailed in Chapter 2. The different classes of monitoring mechanisms require individual configurations of the client- and server-side. Consequently, AdaptMon.KOM is also split into client- and server-side components. We focus on the client-side components during the explanation of AdaptMon.KOM in the following sections. Monitoring allows for the observation of mechanisms, protocols, and applications, as well as environmental factors. For better readability, we refer to the monitored entities as *systems* in the following.

5.2 SEPARATION OF THE MONITORED SYSTEM AND THE MONITORING MECHANISM

To allow for *i)* the monitoring of different mechanisms and *ii)* transitions between monitoring mechanisms, the design of AdaptMon.KOM focuses on the separation of monitored systems and the monitoring service itself. The separation of the monitoring service from the systems used in the network requires a well-defined interface between the monitoring service and those systems, to allow for information retrieval. However, as seen in Chapter 3, current monitoring approaches either assume the requested information to be available for the monitoring effort [82, 164], thus not considering the information measurement process. Or, the systems used in the network perform the monitoring individually [119, 199], leading to a tight coupling between monitoring mechanism and monitored system.

Separation to allow for transitions...

The measurement of information is a non-trivial task in the dynamic environment of mobile networks. We propose our solution allowing for independent measurements with the State Information System (SIS) in [154, 155]. Both the SIS and AdaptMon.KOM rely on requests and responses to allow systems to obtain information as shown in Figure 14. We use two dimensions for the separation, covering the four main phases of monitoring (see Section 2.3): *i)* the separation of the measurement from the systems using the Monitoring Access Points (MAPs) abstraction and *ii)* the separation of the monitoring from the systems. The SIS is based on a provider and consumer concept in which MAPs are used to access systems on the different layers of the protocol stack [154, 155]. In doing so, we map the measurement phase of the monitoring process. The provider and consumer concept and the MAPs are detailed in the following.

Systems containing information provide these through the MAPs to the SIS registering as an information provider. MAPs are used to access the systems on different layers. For this, the mechanism implementations must be modified with the `provide` method of the SIS. The `provide` method is necessary to allow for active retrieval of information. Otherwise, the local measurement would be limited to passive observation, resulting in inaccurate monitoring of the network systems [6, 98, 154]. Systems declare information they want to `provide` as `SiSType`.

```
SiS = host.getComponent(SiSComponent.class);
SiS.provide().nodeState(SiSType<T> type, SiSDataCallback<T> dataCallback)
```

... & to use a joint data basis.

Systems that registered as information provider with the SIS (see Figure 14) can act as data sources for later requests. An information provider can `revoke` the availability as a data source if desired. As systems can `provide` and `revoke` being a data

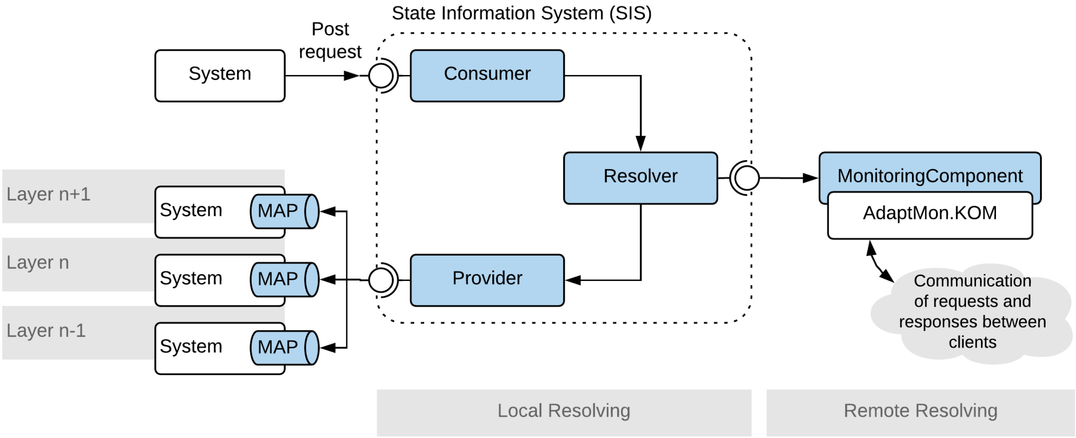


Figure 14: Separation of the monitoring service and the monitored systems using MAPs to access systems layer-independent. The SIS takes care of communicating requests and responses between the systems and, if needed, the monitoring service.

source, the measurement process of information itself is transition-independent. Still, information might not be available after a transition anymore. Information consumers post requests to the SIS. The request is handled by the resolving component which evaluates whether received requests or responses are of interest for this client. If the request is not resolvable locally on the client, e. g., the request asks for data from remote clients, the currently used resolver logic (see Figure 14) forwards the request to the `MonitoringComponent`, in this case AdaptMon.KOM. The request is then resolved remotely by the `MonitoringComponent` following the four phases of monitoring as introduced in Section 2.3. We detail the remote resolving, which incorporates communication between the clients, in Section 5.3. Incoming requests and responses from other clients are forwarded to the SIS and handled by the resolver component. Requests are checked for validity and whether they can be answered or enriched with information by the receiving client, such as adding aggregated information.

Request resolving

Requests contain the following fields: the requested metric (`SiSType<T>`), the type (`RequestType`), its `scope`, its `validity`, and an optional `AggregationFunction`. Those fields (except of the validity field) form a unique identifier for hash-based comparison of requests in the network. The goal of a request is to match remote entities that are registered as information providers with the SIS. By specifying the `RequestType`, systems can state whether they require the respective metric *i)* only once (one-shot), *ii)* periodic with a given interval, or *iii)* event-based, i. e., based on a condition that triggers an update. The scope specifies if the request targets a subset of clients, i. e., those that match filter operations, or if the request is valid for all monitored entities. Optionally, the `AggregationFunction` can be provided by the requesting application to allow for custom data aggregation within AdaptMon.KOM.

Content of a request

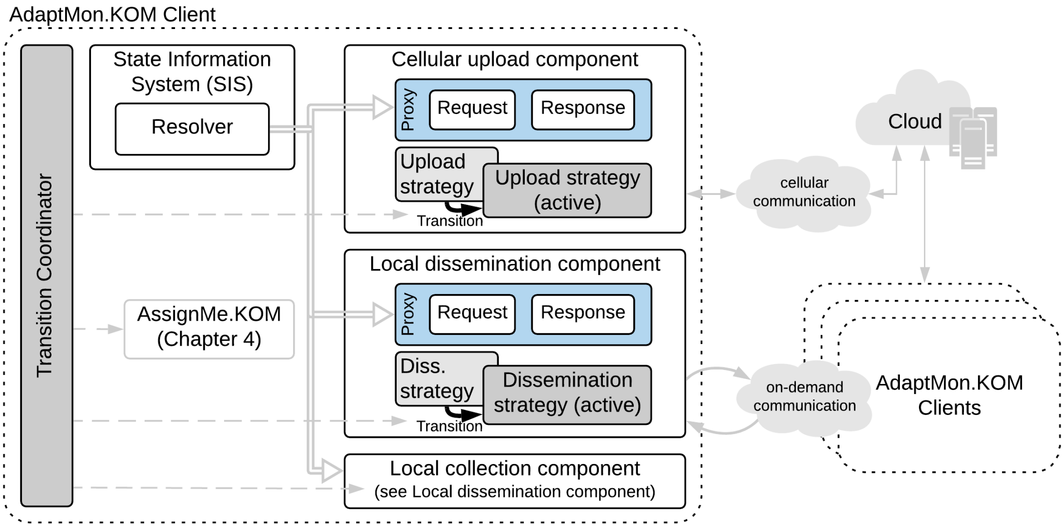


Figure 15: Mapping of monitoring functionality in AdaptMon.KOM. Proxies for communication mechanisms allow for transitions between monitoring approaches.

In summary, the separation of monitoring from the systems relying on the SIS and the MAPs concept allows for *i)* system independent information retrieval, enabling a first step towards transitions. Furthermore, *ii)* a shared information basis is built, which can reduce the latency of the information retrieval significantly and also reduce the costs introduced by monitoring. With the separation, the monitoring service is able to adapt to changes which occur frequently in mobile networks and environments.

5.3 MAPPING OF MONITORING FUNCTIONALITY

Local resolving is based on the SIS with MAPs at the individual systems on each layer. Whenever requests require more than local measurements of information, remote resolving is triggered. Remote resolving incorporates communication between clients to resolve the requests in the network, constituting the main part of AdaptMon.KOM. The monitoring service needs to adapt to network dynamics to provide reliable and accurate monitoring [155–157, 162]. To allow for transitions between monitoring approaches, AdaptMon.KOM must be able to represent the approaches of the monitoring classes identified in Section 3.1. Based on the analysis of the current state-of-the-art monitoring approaches in Section 3.1, we identified the communication patterns as the distinctive characteristics of monitoring approaches. Centralized, hybrid, and decentralized monitoring approaches all comprise of different communication patterns. Accordingly, AdaptMon.KOM contains components that correspond to these patterns.

Encapsulation of distinctive characteristics

On mobile clients, three components are responsible to communicate monitoring information as visible in Figure 15: *i)* cellular upload, *ii)* local dissemination, and *iii)* local collection. These components are used together with the connection to the SIS (i. e., the resolver component) and the local measurement facilitated by the MAPs to allow for cross-layer monitoring. We rely on transition-enabled proxies, as detailed in

Section 2.5, as abstraction enabling transitions between monitoring approaches. The usage of the proxies within AdaptMon.KOM is detailed in Section 5.4. The proxies encapsulate the functionality of the communication patterns behind a common programming interface for both requests and responses as visible in Figure 15. Proxies implement the `TransitionEnabled` interface to provide for basic life cycle controls. To explain the usage of the proxies, we will detail an exemplary workflow of a request posted to AdaptMon.KOM configured as decentralized monitoring approach relying on flooding. In this case, the request is not resolvable locally and is forwarded by the resolver to the respective local dissemination proxies. As AdaptMon.KOM is configured as a flooding-based decentralized monitoring approach, only the local dissemination proxies are used for communicating both requests and responses. The local dissemination proxies contain the `disseminate` method that handles requests.

```
LocalDissemination.disseminate(msgId, payload,
    LocalDisseminationPayloadType, LocalDisseminationFlag);
```

The payload contains the request, the `LocalDisseminationPayloadType` is set accordingly to highlight that this message contains a request. The `LocalDisseminationFlag` details if the payload is intended for local on-demand communication only or if it is allowed to be uploaded via cellular communication when received by other clients. This flag is needed to prevent data from being up- and downloaded multiple times, which may otherwise happen in hybrid configurations of AdaptMon.KOM. The request is then disseminated as a `LocalDisseminationMessage` by flooding it to other clients. On receiving clients, the `LocalDisseminationMessage` is handled by the local dissemination proxy. Depending on the currently active mechanism, the received request is forwarded in the network and/or handed over to the resolver component in the SIS. The resolver checks if this request is still valid and if the receiving client can satisfy it. The receiving client builds a response containing the requested information. Responses include the requesting client, the unique identifier, the validity, and the aggregation function from the request in addition to information collected from other clients. The response is then handed over to the communication proxies, which take care of returning the response to the requesting client. In this case, with the flooding-based decentralized monitoring, the local dissemination proxy will broadcast a `LocalDisseminationMessage` containing the response in the network. Other clients, aware and targeted by the request, that overhear the message add own information. By flooding the network, this reply eventually reaches the requesting client.

Mapping a multitude of monitoring approaches

Relying on its proxy-based communication structure, AdaptMon.KOM is able to map a multitude of monitoring mechanisms, without being limited to the mechansims discussed in Section 2.3. The proposed hybrid monitoring mechanism [156, 157, 162] depicts a hierarchical topology that uses gateways for communication with a cloud-based server. For the selection of gateways, we rely on AssignMe.KOM as detailed in Chapter 4. Non-gateway clients are overhearing advertisements from gateways, connecting to them using a multi-hop, contention-based forwarding scheme [103, 212]. The mechanism shows improved usability concerning the range of conditions it can be applied to. Table 1 shows the proxy configuration of the proposed mechanism [156, 157, 162] and the proxy configurations for other monitoring mechanisms.

		Proxies for Request/Response			Server Proxies
Monitoring Approach		Local Dissemination	Local Collection	Upload	Dissemination
Centralized		none	none	direct	direct
Hybrid [157, 162]	Req.	none	none	direct	direct
	Resp.	none	contention	gateway	gateway
Hybrid [161]	Req.	broadcast	contention	gateway	gateway
	Resp.	broadcast	contention	gateway	gateway
Decentralized (flood)		flooding	flooding	none	none
Decentralized (DTN)		epidemic	epidemic	none	none

Table 1: AdaptMon.KOM client and server proxy configurations to illustrate the mapping of different monitoring approaches (extract).

5.4 transitions between monitoring schemes

As introduced before, we rely on transition-enabled proxies as abstraction allowing for transitions between monitoring mechanisms. We identified the communication patterns as the distinctive characteristic of network monitoring mechanisms (see Section 5.3). Transitions between mechanisms are controlled by the transition coordinator component on the client (see Figure 15), as explained in Section 2.5. As a reminder, each strategy has to implement basic life cycle methods as defined in [67, 148]. The life cycle methods ensure atomicity of a transition execution, thus guaranteeing that transitions are either executed correctly on the respective components or nothing is changed at all. As defined in Section 2.5, a transition on proxy X, targeting a set of clients C ($C \in \{c_1, c_2, c_3, ...c_n\}$) between strategy A and B is denoted as $T_X^C : A \rightarrow B$.

A transition which targets the executing client itself is referred to as self-transition $T^\bullet$. We use self-transitions to change parameter configurations on a client for local adaptation on changes. Transitions targeting a group of clients C ($C \in \{c_1, c_2, c_3, ...c_n\}$) are denoted with T^C. A global transition $T^\forall$ is used when all clients in the network are targeted. Transitions, as said before, may use filter functions to further describe the set of targeted clients with more detailed attributes, such as location or battery power. As both T^C and $T^\forall$ target foreign clients from the viewpoint of the origin client, a spreading of the transition decision in the network is crucial. In the following we detail *i)* how a transition is executed and *ii)* how the decision is spread in the network.

5.4.1 *Execution of Transitions*

The decision process for a transition is not part of AdaptMon.KOM. However, the monitoring service design considers that every entity can decide on a transition. We assume that transitions within AdaptMon.KOM originate from trusted entities. For a transition on client c_i from strategy A to B ($T^c_{proxy} : A \rightarrow B$), it is crucial that relevant and supported state of strategy A is transferred to the following strategy B. Two types of state transfers are required. The state transfer can either be intra-proxy, i. e., in one proxy between the used strategies [67, 148], or the state transfer is inter-proxy as visible in Figure 16. In both cases, state transfer does not include any additional communication between clients as otherwise the atomicity of transitions cannot be guaranteed. We propose the inter-proxy state transfer in this work. Consequently, state transfer is no longer limited to mechanisms within one single proxy, which is an essential step in supporting transitions between entirely different mechanisms, such as centralized and decentralized monitoring structures.

Inter-proxy state transfer . . .

For intra-proxy state transfer, we rely on the annotation concept as introduced in [67, 148]. Based on this concept, state of the origin strategy can be relayed to the following strategy during the life cycle of transitions (see Section 2.5). State that possibly can be transferred is annotated with:

```
@TransferState(value = { "FieldValue" }).
```

Here, the state of `FieldValue` is transferred from strategy A to strategy B using the `setFieldValue` method that must be provided by the strategies (see Section 2.5).

Knowledge about requests and responses within AdaptMon.KOM is stored in the active proxies of the communication components. Transitions between different monitoring mechanisms can result in some proxies being switched off entirely. Thus, when executing transitions between different monitoring approaches the loss of information on requests and responses is possible. We take the transition on client c_i from decentralized (flooding-based) to centralized monitoring (see Table 1) as an example to explain the usage and need of inter-proxy state transfer. The transition plan consists of the following transitions:

. . . to overcome state loss during complex transition plans.

1st Local Dissemination Proxy:	$T^{C}_{\text{locDiss}} : \texttt{flooding} \rightarrow \varnothing$
2nd Local Collection Proxy:	$T^{C}_{\text{locColl}} : \texttt{flooding} \rightarrow \varnothing$
3rd Upload Proxy:	$T^{C}_{\text{up}} : \varnothing \rightarrow \texttt{direct}$
4th Server Dissemination Proxy:	$T^{C}_{\text{serDiss}} : \varnothing \rightarrow \texttt{direct}$

Both proxies for local communication are switched off for the transition to centralized monitoring. Thus, stored requests and responses would be lost after the transition, which in return can cause a significant drop of the accuracy and reliability of AdaptMon.KOM. To overcome this limitation, we introduce the inter-proxy state transfer realized with a persistent storage component within the transition framework. Concerning the exemplary transition plan above, a pre-defined state can be handed over to another proxy. Thus, the currently known requests and responses in both local communication proxies can be handed over to the upload proxy to prevent a loss of data during the transition between the two monitoring mechanisms. However, to allow for successful state transfer between different proxies, a predetermined order of transitions must be satisfied as otherwise the required state cannot be obtained before transferring to the other proxy.

In the following, we detail the formalization of this process, presented in our previous work [155], on the example of a general transition plan consisting of two transitions. One transition is executed within proxy X and another one within proxy Y. The fol-

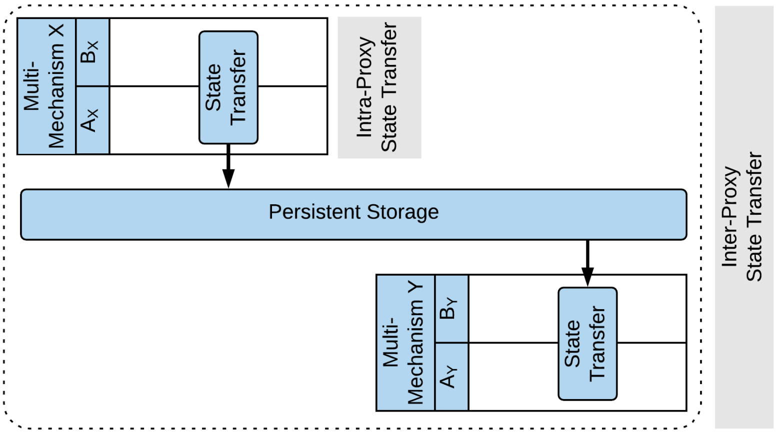


Figure 16: Intra- and inter-proxy state transfer in AdaptMon.KOM.

lowing attributes must be specified for the transitions $T_X^C : A \rightarrow B$ on proxy X and $T_Y^C : C \rightarrow D$ for proxy Y:

```
transferState(proxy X<M∅ → BX>, proxy Y<M∅ → DY>, Set<stateVariable>)
```

Using the `transferState` method ensures that the state between proxies X and Y is only transferred when: (i) a transition on proxy X to strategy B_X and (ii) a transition on proxy Y to strategy B_Y are planned for the same point in time in the transition plan. Similar to the intra-proxy state transfer, variables for the `transferState` method must be annotated and the strategies must provide a setter method. If this is the case, the given set of state variables is transferred between the two proxies X and Y.

As it cannot be guaranteed that transition decisions reach all affected clients, the spreading of the former must be taken into account, which is detailed in the following.

5.4.2 *Spreading of Transition Decisions*

The transition type (see Section 2.5) determines if the transition decision must be spread to other clients in the network. Spreading is needed if the transition is of regional or global type. For the spreading of transition decisions, C/S approaches have been considered so far in the assumption they provide reliable spreading [148, 167, 199]. Considering the dynamics of mobile networks, the usage of C/S approaches may not be feasible as seen in Chapter 2 and Chapter 3. Mechanisms like self-healing, help to overcome potential incompatibilities by synchronizing transition decisions among clients [148, 155].

Low overhead transition spreading

To handle network dynamics naturally, assuming mechanisms at hand are transition-enabled and will allow for communication, we integrate a piggybacking strategy to the Simonstrator.KOM. This piggybacking strategy appends known transition decisions to messages sent from clients in the network. For that, the `piggybackOnSendMessage` method is used, which automatically appends the transition decision to a given protocol at the transport layer.

```
Message piggybackOnSendMessage(NetID to, int receiverPort,
    TransportProtocol protocol)
```

In doing so, transition decisions spread throughout the network using the principles of DTNs. The reason for that is, that frequent local communication is present in the communication network which helps spreading the transition decision without any overhead in the form of additional messages [168].

5.5 COLLABORATIVE MONITORING FOR LOCATION-BASED SERVICES

Combining monitoring & role assignment

The transition-enabled monitoring service AdaptMon.KOM and the adaptive offloading service AssignMe.KOM, presented in Chapter 4, allow for new application fields. A multitude of applications for current and future Internet scenarios, e. g., the IoT and augmented reality games, rely on frequent and accurate position updates of users. Many of these applications from the class of location-based services are implicitly bound to the users and their surroundings. The requirement for frequent and accurate position updates imposes two main challenges. First, different localization technologies such as GPS, Wi-Fi or cellular triangulation offer various accuracies, thus, providing the required accuracy can be difficult. Furthermore, erroneous sensor readings may further decrease the accuracy. Second, with frequent individual location measurements, the acceptance of the location-based service shrinks as every accurate location measurement is a battery-intensive task [194]. Especially on the resource-constrained clients used in the mobile networking domain, high battery usage or similar wasteful resource allocations are undesired (see Section 2.1).

As seen in Section 3.1, current approaches for location retrieval in mobile wireless scenarios rely on fingerprinting, geometric estimations [82], or local sharing of positions between clients that have access to accurate positions and those who have not [113, 181]. These mechanisms have one thing in common: they pursue a given utility function—mostly providing accurate position estimations—while not considering introduced cost or the fairness of consumed resources on mobile clients. Additionally, many of the approaches rely on measurements by every client. Thus, the approaches assume the availability of localization technologies, irrespective of the accuracy or cost of the specific localization technology.

Benefit from collaboration for location retrieval

To this end, we designed a collaborative monitoring mechanism for location-based services [153] to target the joint consideration of *i)* position accuracy, *ii)* cost-awareness, and *iii)* fair usage of resources within location retrieval in mobile wireless scenarios. This example showcases the benefits and flexibility of the coexistence of transition-enabled offloading and monitoring services. Instead of relying on every client's measurements, our approach selects a subset of clients as anchors for cost-intensive location measurement, which results in a reduction of the overall induced cost [153]. To still allow for accurate position estimations of all clients, we use connectivity information obtained by the clients in the network.

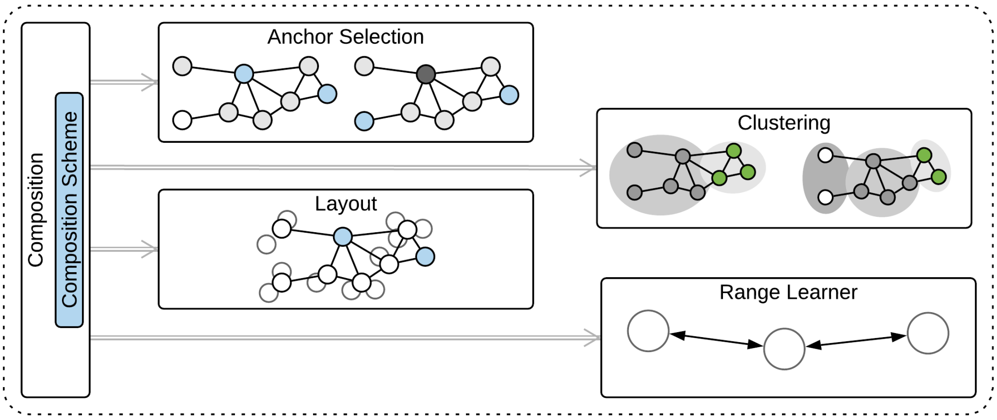


Figure 17: Main components of the collaborative location retrieval service. Partially based on a combination of AdaptMon.KOM and AssignMe.KOM.

Benefit from Collaboration within Monitoring

The combined mechanism allows for different compositions of its components to pursue various utility functions for location retrieval, such as low energy usage, fair resource consumption, or high accuracy [153]. The ability to pursue different utility functions is necessary as the requirements on the location-based services may vary. Based on the analysis of current location estimation approaches (see Section 3.1), our mechanism consists of the five main components shown in Figure 17. The *anchor selection* and *clustering components* are responsible for determining anchor clients and represent the most influential components concerning the utility function of our combined mechanism. In the *layout component*, the location measurements of the selected anchor clients are combined with the connectivity information obtained by the clients to estimate each client's location. With no knowledge about the receiving range of the communication means used to obtain the connectivity graph, the *range learner component* is used to learn the maximum communication range over time. Different service compositions—also allowing for multiple utility functions—are organized within the *composition component*. The details of the components are outlined next.

Anchor Selection and Clustering

In the mobile networking domain, especially in the area of offloading applications, selection and clustering of clients is highly relevant [11, 147]. However, most approaches used for selection and clustering rely on recent position measurement of all clients. Concerning this limitation, we rely on applicable selection strategies, such as energy-aware approaches [78, 140] and propose selection strategies for the use case of location estimation. These selection strategies use information gained from a connection graph of an underlying communication means or information that is already available on

Selection Strategy	Description
Negative Interference (NegInt)	Selects the best-connected client as anchor and removes all directly connected clients from the list of potential anchors.
Cluster Corner (ClusCor)	Chooses anchors from the outside (no location information is used) of a calculated cluster resulting in non-anchor clients being surrounded by anchor clients. The knowledge on the boundary of the area spanned by selected anchors can reduce the offset of the estimated locations.
Minimum Cost (MinCo)	Reduces the number of cost-intensive active location measurements and the number of cost-intensive measurement state changes of the clients. Thus, selected anchors are used for a multiple successive measurements.
Fair Cost (FairCo)	Selects few anchor clients to reduce the introduced cost in each measurement round. In contrast to MinCo the selected anchors are, changed more frequently over time to obtain a fair distribution of the load.

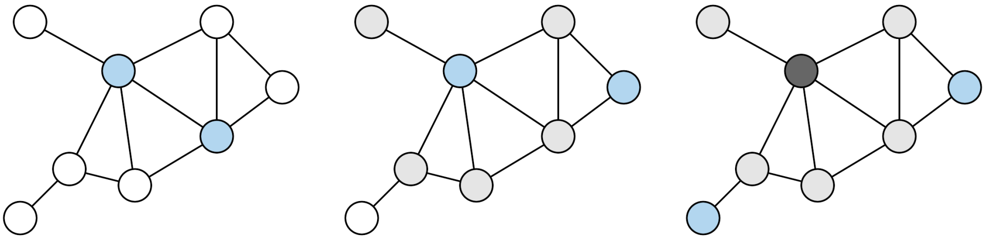
Table 2: Anchor selection strategies used in the collaborative monitoring mechanism for location-based services.

the clients through AdaptMon.KOM to avoid costs that would arise from additional measurements. We highlight four selection strategies, which are explained in the following, in Figure 18. Blue colored clients are anchors selected by the strategy. Gray and dark gray colored clients are excluded from the list of possible anchor clients from the used strategy in the process of the selection.

To allow for accurate position estimations based on connectivity information the usage of well-connected clients seems beneficial. Selecting those well-connected clients is related to the centrality metric in social networks described by Freeman in [65] and VIP-selection strategies presented in [11]. Thus, the initial idea is to select those clients as anchors that are well connected to other clients and central according to [65] in the connectivity graph. This selection causes anchors to have many adjacent clients, potentially resulting in lower offsets for the estimated positions. However, we observed that this selection leads to strong offset variations of the estimated positions on the edge of the connectivity graph. As initial evaluation results revealed, this is due to the very dense population of anchor clients around the detected central point of the connectivity graph, reducing the accuracy at the edge of the connectivity graph significantly [153]. Figure 18a supports this finding as both anchors are direct neighbors. On a large scale, this leads to a high density of anchors in certain areas of the connectivity graph without providing the needed distribution of anchors for better localization. Based on this finding we developed the following selection strategies.

Negative Interference (NegInt) Selection Strategy

The NegInt selection strategy selects the best-connected client as an anchor from the list of connected clients. To overcome the challenge of densely populated anchors, NegInt removes all clients with a direct connection to the selected anchor client in the



(a) Max connection selection (b) NegInt selection (c) ClusCor selection

Figure 18: Anchor selection strategies of AssignMe.KOM used in the combined approach (excerpt). Blue colored clients are selected anchors. Gray and dark gray colored clients are excluded from the list of possible anchor clients from the used strategy.

connectivity graph from the list of potential anchors. Thus, the distance between two adjacent anchors is at least two hops, but still provides a sufficient number of anchors in densely populated areas. The resulting selection of anchors is visible in Figure 18b. This scheme allows for a density-aware coverage of the anchors in the network.

Cluster Corner (ClusCor) Selection Strategy

Instead of choosing anchors beginning with the best-connected clients the ClusCor selection strategy chooses anchors from the outside of a calculated cluster. This results in non-anchor clients being surrounded by anchor clients. The area spanned by selected anchors in ClusCor can be used to reduce the offset of the estimated locations using the knowledge of the boundaries of the areas, i. e., the locations of the anchors. However, the ClusCor strategy is not using location information to select the anchors at the corners of the cluster. We rely on the findings of Kang et al. [94], who found a correlation between the number of connected neighbors of a client and its distance to the center of a cluster. Accordingly, we start from the best-connected client(s) in the obtained connectivity graph and exclude these client(s) and their neighbors. In best case, a ring of clients around the excluded client's forms, which we use as the initial set of potential anchors. The process of excluding clients with neighbors can be continued from there on. In the current design of ClusCor, we stop this process after three iterations, which is sufficient for most location-aware clusters prevalent in mobile networks according to [18]. Figure 18c shows the basic idea of ClusCor. Instead of selecting the central dark gray client this strategy selects the clients far away from the center of the connectivity graph.

Minimum Cost (MinCo) and Fair Cost (FairCo) Selection Strategies

Targeting coverage optimization, NegInt and ClusCor do not consider the cost introduced by the selection of anchors. For this, we proposed the MinCo and FairCo anchor selection strategies in [153]. The MinCo strategy reduces *i)* the number of cost-intensive location measurements (i. e., active measurements) and *ii)* the number of measurement state changes of the clients (i. e., the frequency with which cost-intensive sensors such as GPS are turned on and off). Continuous measurements with, e. g., GPS are less energy consuming than starting the GPS measurement on different clients each time, which results in more location fix states that consume more energy [139, 210]. The load for the measurement task is not distributed in a fair manner as MinCo focuses on the reduction of measurement state changes. The resulting continuous measurements are less expensive but imply an uneven share of the measurement task among clients. In a collaborative approach, a fair share of the overall load is intended [43, 83, 206]. Overall longer client lifetimes are also a result of a fair distribution of tasks. We target these limitations in the FairCo selection strategy. Similar to the MinCo strategy, few anchor clients are selected to reduce the introduced cost in each measurement round. The selected anchors are, in contrast to MinCo, changed more frequently over time. This allows for a fairer resource utilization of the clients in the FairCo strategy.

Cost- & fairness-aware anchor selection

Clustering Strategies

We use clustering strategies in our combined mechanism to split the complete connectivity graph into smaller sub-graphs. In doing so, potentially more accurate position estimations can be obtained as subsequent computations, e. g., anchor selection and layout, are performed on a regional graph structure. For the clustering, we rely on the following three strategies of AssignMe.KOM (Chapter 4): *i)* a variant of the density-based clustering algorithm DBScan [62], called Connection based Clustering (CBC), *ii)* the partition-based k-Means++ [4], and *iii)* a grid-density-approach, which builds upon [47]. Changes to the original DBScan algorithm were necessary as some clients were classified as noise, which is contradictory to the requirement to provide for location estimations of all clients in the network. To overcome this, clients that are not assigned to a cluster build their individual one-client clusters, enabling the reliable selection of anchors per-cluster for all clients. Furthermore, CBC starts with the best-connected client unlike a random sampling used in the initial design of DBScan in [62]. This is followed by an iteration in descending order of the number of connections over each client within CBC. If a cluster is found in the direct one-hop neighborhood of a client, it is affiliated to this cluster. If no affiliation is possible, a client is assumed to be part of its own cluster, again guaranteeing position estimates for all clients. Based on the assumption that well-connected clients are very likely together in a cluster, CBC starts with the best connected client. By iterating outwards, all clients belonging to that cluster are gathered, ensuring clients that are closer to another. Equally well-connected clients are assigned respectively.

Clustering of non-anchors to anchors

The Layout of a Connectivity Graph

After a subset of clients are selected as anchors using the selection and clustering strategies detailed above, those clients measure their position using a localization method such as GPS or Wi-Fi triangulation. The gained location information is combined with the one-hop connectivity information of all clients, which results in an annotated connectivity graph for each cluster, or for the whole network when no clustering is used. In both cases, it is possible that the resulting connectivity graph is partitioned. For the estimation of client locations, based on the fusion of few position measurements and underlay connectivity information, we rely on so-called layout algorithms. We use a spring force layout algorithm based on [68, 135] and a layout algorithm proposed by Kamada and Kawai in [92]. In both layout algorithms, however, distance estimations between clients without a connection but with line-of-sight must consider the maximum communication range of the used communication means. Thus, the distance estimation of connected clients cannot be longer than the maximum communication range of the underlying communication means. Anchor positions are fixed in the layout, while the estimated positions of non-anchor clients are moved after forces have been calculated by the algorithm for each client.

Layout of an annotated graph

According to Fruchterman et al. [68], the calculation of forces and the following replacement of clients in the layout is referred to as *step*. The layout algorithms terminate after a given number of steps, due to the assumption that the algorithms reach steady state. After termination, the layout algorithm returns the annotated graph including the estimated positions for the non-anchor clients. In contrast to [68], we do not take repulsive forces into account. We iterate once over each pair of clients, without repetition. If clients have a connection, only attractive forces are computed. In case a pair of clients has no connection, we calculate repulsive forces only if the distance between both is shorter than the currently assumed communication range. The assumed communication range is provided by the range learner component introduced later. With this modification of the algorithm, we can drastically reduce the computation overhead of the method as pairwise relations are considered only once. The resulting complexity for n clients per step is given by Equation 3:

$$\sum_{i=1}^{n-1}(i) = \frac{(n-1)^2 + (n-1)}{2} \in \mathcal{O}(n^2) \tag{3}$$

Estimate positions by step-based calculation of forces

In [135], a single force multiplier σ is used to estimate the positions of clients in the graph. However, client distances do not necessarily behave like actual springs. The likelihood for connected clients being closer together than the assumed maximum distance is larger than the likelihood for them being much further apart. This means that the utilized spring forces are non-uniform. To depict that, we do not use a single force multiplier like the authors of [135]. Instead, we rely on three forces to improve the approximation accuracy of client locations and distances. For connected clients that are closer together than the average of all distances in the connectivity graph, $\sigma = 0.1$ is used. In the case of connected clients whose estimated distance is larger than the maximum communication range, they must move together. Thus, a σ of 0.8 is used. If the distance between connected clients is *i)* larger than the average and *ii)* smaller than the maximum communication range a σ of 0.3 is used. For unconnected clients being closer together than the maximum communication range, $\sigma = 0.3$ is also used. In such cases, the desired distance is at least the maximum communication range obtained from the range learner component.

$$\mathcal{F}(d_{A\leftrightarrow B}) = \frac{d_{\text{desired}} - d_{A\leftrightarrow B}}{d_{A\leftrightarrow B}} \tag{4}$$

The force multiplier σ for the distance between two clients A and B ($d_{A \leftrightarrow B}$) multiplies with the *distance dependent force* $\mathcal{F}(d_{A \leftrightarrow B})$, seen in Equation 4. As clients with higher degree tend to drag their connected clients to another position, referred to as *slingshot*, we split the resulting forces between clients A and B inverse proportionally to their respective number of connections [153]. In doing so, we prevent that a slingshot of a high degree client in layout step i results in a drag of all connected clients in the following layout step $i + 1$.

Learning the Communication Range

Grasping environment constraints in the estimation process

As mobile clients may venture into areas with different environmental interference on the used communication means, the possible ranges assumed for device-to-device communication can change over time. Regarding the heterogeneity of clients, there might also be differences between client types. To improve the adaptability to environmental changes and to reduce inaccurate initial assumptions, learning of possible communication ranges is important within the collaborative location retrieval mechanism. However, we limit the process to any information that is directly available from the connectivity graph and the location information gained from anchor clients to not further increase costs. With a limited number of accurate position measurements retrieved from the anchors, the estimated positions from the layout are also used for the process of learning the communication range, even if this information is biased. We use a No Learning (NL) baseline in combination with two different learners. Our learners rely on filter methods used, for example, in the domain of signal processing [129, 192]. We try to minimize the effects of jitter values from the input and, therefore, use low pass filtering methods.

The Exponential Smoothing (ExpSmo) algorithm uses the estimated communication range from the former layout step i_{t-1} and takes it into account for the current layout step i_t. In the ExpSmo algorithm, the estimated distance e_t for step i_t is computed as seen in Equation 5:

$$e_t = \alpha \cdot d + (1 - \alpha) \cdot e_{t-1} \tag{5}$$

The current estimated distance is represented by d, while α symbolizes a weighting factor of the ratio of the current e_t over e_{t-1}. Similar to the ExpSmo algorithm, we use the Autoregressive Filter (AutReg) algorithm. The difference between the two is that AutReg uses the previous k estimations of e for its computations, shown in Equation 6:

$$e_t = \alpha \cdot d + (1 - \alpha) \cdot \frac{1}{k} \cdot \sum_{i=1}^{k+1} e_{t-i} \tag{6}$$

Those simple learners are used to understand the estimation of the communication range at first. We did not apply artificial intelligence techniques in this first step to understand how the distance estimation behaves per step.

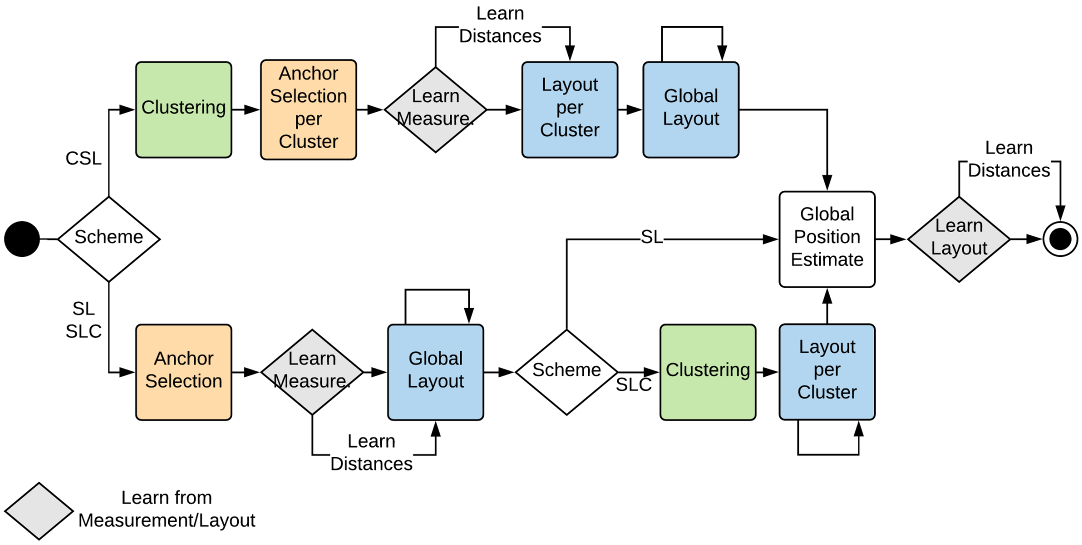


Figure 19: Composition schemes used in the collaborative location retrieval mechanism.

Composition to Allow for Adaptivity

Our proposed combined mechanism enables the joint consideration of *i)* position accuracy, *ii)* cost-awareness, and *iii)* fair usage of resources during location retrieval in mobile wireless scenarios. Accordingly, the mechanism needs to allow for different utility functions depending on the given requirements of the location-based services. For that, we use the composition component that determines the order in which the main components are used and combined (see Figure 17). By changing the execution order of, e. g., anchor selection and clustering, the accuracy of the position estimations is affected. The anchor selection can, for example, rely on a per-cluster basis instead of selecting anchors first and then building clusters around them. The layout can be used on a per-cluster basis to reduce the computational load or for all clients (including potentially unconnected graphs) once. Using different combinations and settings allows for a variation of utility functions. As anchors are clients that perform actual location measurements, the anchor selection strategies NegInt, ClusCor, MinCo, and FairCo are the main influencing factors for the accuracy and the introduced costs of our solution. In the following, we detail the three main composition schemes, visualized in Figure 19.

Composition to enable multiple strategies

The first scheme, Select-and-Layout (SL), relies on anchor selection followed by a layout of the connectivity graph with the selected anchors. This scheme does not use clustering strategies to split the graph, e. g., before selecting anchors, as seen in Figure 19. The Cluster-Select-Layout (CSL) composition clusters the connectivity graph in a first step. The clustering can use one of the presented approaches DBScan [62], k-Means++ [4], grid density [47], or the proposed CBC approach (see Figure 5.5). The initial clustering is followed by the selection of anchors in each cluster. After the clustering and anchor selection, the CSL composition executes the layout in each cluster with an a-priori given number of steps. Afterwards, it merges the individual results per cluster to one connectivity graph on which we perform a final layout. This process is visible in the upper branch of Figure 19. This reduces the potential of unlikely placement decisions, such as multiple clients in a cluster being placed on the same location. The last composition scheme is Select-Layout-Cluster (SLC), which is similar to SL. However, after SL is finished, SLC adds an additional clustering step and a layout per cluster to the process chain. This additional clustering and layout are done to refine the location estimations after the initial results gained from SL. In doing so, we are able to prevent negative side effects caused by clients far away from a cluster. The aforementioned learning mechanisms for communication ranges can optionally be used (see Figure 19).

Combining offloading and monitoring for new application domains

Overall, the combined approach for location retrieval, as presented in [153], shows the potential of combining transition-enabled services. By combining the information gained from ADAPTMON.KOM and the techniques of selection and clustering from ASSIGNME.KOM, configurable collaborative location retrieval can be realized. By design, the service is reducing the resource demand on the clients to retrieve location information for all clients in the network. Additionally, the characteristics of the service allow for applications in the domain of privacy and intrusion detection as the collaborative nature of the connectivity graph can be used to detect, e. g., misreported locations. Last but not least, due to the sensor fusion used in our approach the accuracy of current state-of-the-art measurement methods can be improved without introducing significant additional cost. We show those benefits in Chapter 6.

6

EVALUATION OF TRANSITIONS WITHIN MONITORING AND OFFLOADING

We propose a novel transition-enabled monitoring service and offloading mechanisms in this work. To evaluate their characteristics and the benefits and costs of transition execution we rely on the simulation-based evaluation of our main contributions AssignMe.KOM and AdaptMon.KOM. Relying on prototypes within the Simonstrator.KOM, we conduct an extensive evaluation showing the use of mechanism transitions in the domains of application monitoring and network offloading. Additionally, we highlight the relevance of key design parts such as inter-proxy state transfer and transition decision spreading that enhance the usability of mechanism transitions in the mobile environment. Section 6.1 includes the main details for the setup of the evaluation. It contains the explanation of the event-based simulation platform Simonstrator.KOM in Section 6.1.1. Furthermore, we detail the impact of mobility models, and their potential influence on the communication means in mobile network research in Section 6.1.2.

Transitions in offloading & monitoring

Transition coordination & spreading

We rely on the implemented prototypes of the concepts explained in Chapter 4 and Chapter 5 with the evaluation. We aim to assess the impact of transitions and their execution during runtime on the adaptivity achieved within monitoring and offloading of mobile networks and applications. We evaluate the potential of transitions between gateway selection and clustering strategies of offloading mechanisms based on our prototype AssignMe.KOM and within the transition-enabled monitoring service AdaptMon.KOM. We examine transitions between monitoring mechanisms in great detail in Section 6.2. There, we also analyze the coexistence of transition-enabled mechanisms. Finally, in Section 6.3, we combine both concepts on the example of a collaborative monitoring mechanism for location retrieval in the scenario of location-based services, as detailed in item 5.5. We focus on *i)* the coexistence of both transition-enabled services and the resulting dependencies between them and *ii)* the characteristics of the collaborative monitoring mechanism. For brevity and better understanding throughout the evaluation, we analyze transitions of gateway selection and clustering mechanisms within AssignMe.KOM and their potential to reflect changing needs in the transition-enabled offloading service in Appendix A.2.

Inter-proxy state transfer

Coexistence of transition-enabled mechanisms

In order to understand the potential of transitions in both domains, we need to compare the transition-enabled services against static mechanisms. This comparison is essential to characterize and isolate the impact of transitions and needs to be conducted in a reproducible setup. Based on the scenario, as introduced in Chapter 2, the dynamics of applications and the mobile environment must be reflected in the evaluation as well.

6.1 EVALUATION SETUP

Reproducibility of the evaluation setup is essential for the comparison of different compositions of the services. Considering the network size required to depict the dynamics of mobile networks this is very hard to achieve. Hence, we rely on the event-based simulation environment of the SIMONSTRATOR.KOM platform as proposed in [148, 151], which we discuss in the following to evaluate our proposed services and their respective transitions. We introduce the SIMONSTRATOR.KOM and the underlying simulation engine PEERFACTSIM.KOM [189] in Section 6.1.1. We propose additional mobility models for PEERFACTSIM.KOM in [160] to target the scenario of this work, which we detail in Section 6.1.2. To achieve realistic results in the conducted simulations, we utilize a configurable workload model, which we detail in Section 6.1.3. We introduce the network model used in our simulations in Section 6.1.4. We explain the utilized metrics to capture the performance characteristics of the services during network operation and transitions in Section 6.1.5. There, we also explain the main plot types used in the evaluation.

6.1.1 *Prototyping Platform: SIMONSTRATOR.KOM*

The main goals of the SIMONSTRATOR.KOM platform are to *i)* improve the opportunities for collaboration among researchers by allowing for rapid prototyping and loose coupling of components, *ii)* to provide a generic platform for the design of transition-enabled communication systems, and *iii)* to support simulation-based evaluations as well as prototypical deployments according to [148, 151]. The Java-based SIMONSTRATOR.KOM platform contains three main building blocks as visible in Figure 20. The *core framework* allows for the design and realization of distributed communication systems. The SIMONSTRATOR.KOM allows for the usage of different *runtime environments* for the execution of the designed *mechanisms* and their evaluation.

The core framework provides the abstractions needed by distributed systems in two conceptional layers. Scheduling abstraction that provides absolute and relative time is the foundation of applications and systems in the framework. It allows for events and operations in the simulations. This layer additionally contains instrumentation-related interfaces, which can be used for debugging or evaluation purposes. Mechanisms are composed out of different *components* provided by the second layer of the core framework. Components provide platform-specific functionality, such as sensors, or allow for mechanism-related integration of, e. g., service characteristics. Combining multiple components to a *host* allows the realization of complex distributed mechanisms [151].[1] The SIMONSTRATOR.KOM platform relies on runtime environments, which can be a network simulator, an emulator, a testbed, or even a single real-world device. This characteristic is essential in the development of mobile applications as it allows the analysis of one system from multiple different perspectives and evaluations goals. For this, the SIMONSTRATOR.KOM provides runtime environments for Java standalone

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[1] The prototypes and runtime environments developed and used in this thesis are available online at www.simonstrator.com. [Accessed December 24th, 2018]

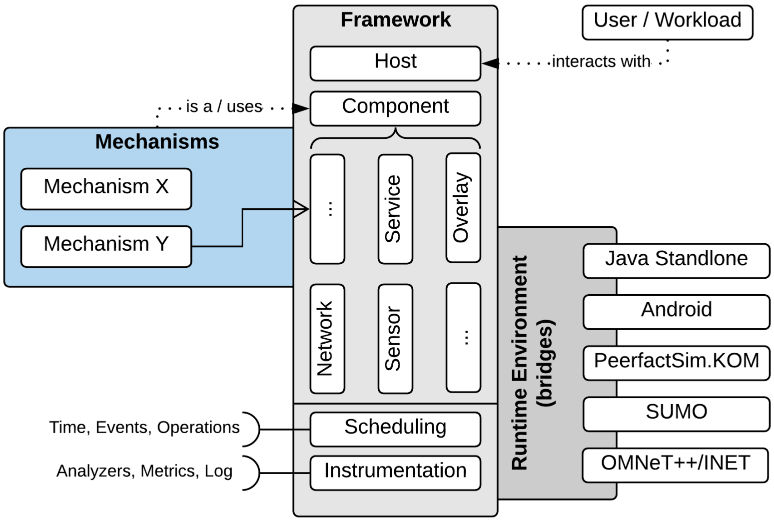

Figure 20: Architecture overview of the SIMONSTRATOR.KOM (adapted from [123, 148, 151]).

projects, Android devices, the overlay simulator PEERFACTSIM.KOM, and the vehicular network simulator SUMO [17]. Furthermore, it allows for external feeds such as the BonnMotion [5] movement generator for mobility traces.

We use the overlay simulator PEERFACTSIM.KOM [189] as the runtime environment for the evaluation of our contributions in this thesis. It allows us to configure the needed variability of the scenarios to cover different aspects of mobile networks. With the runtime environment, we can achieve a scenario of the scale to represent the dynamics of the environment accordingly. To improve the usability of the PEERFACTSIM.KOM runtime environment for highly dynamic mobile social networks we proposed two modular extensions in [160]. As client mobility heavily influences the interaction patterns of the users, we propose a *mobility and social interaction model* that relies on attraction points to model application-specific points of interest. We detail the mobility and social interaction model in Section 6.1.2.

Client mobility & interaction patterns

Furthermore, we add support for heterogeneous connectivity scenarios by allowing for Wi-Fi access points and the resulting handover events between cellular/Wi-Fi infrastructure-based and local infrastructure-less communication. The proposed extension supports cellular connectivity and connections to Wi-Fi access points. Mechanisms are notified by a *handover sensor* (located in the SIMONSTRATOR.KOM) in case of network connectivity changes—i. e. a device changing from the cellular network to Wi-Fi. To allow the usage of information gained from large-scale measurement databases for 5G/LTE networks [97] and urban Wi-Fi APs coverage [111] the extension divides the simulated area into freely configurable cells. For simplicity, we use rectangular cells in this work—however, often used hexagonal cells can also be modeled. For further details on the SIMONSTRATOR.KOM platform and the PEERFACTSIM.KOM runtime environment [189], we refer the interested reader to [148, 151].

6.1.2 *Influence of Mobility on Communication in Mobile Networks*

The interaction between users and the availability of infrastructure-based communication means strongly depend on the location of users. The realistic representation of human motion patterns is therefore important in the scenario considered in this work [34, 95, 131]. In a previous work, we developed a model for mobility and social interaction [160]. The proposed movement model relies on the use of attraction points to model application-specific points of interest. Real-world locations as points of interest incentivize users to approach and interact with these locations; thus, applications affect the movement. Direct interaction between users and friends establishes social connections. Taking a group of friends as an example helps in understanding this influence. A user, who is attracted by an application-specific point of interest, very likely communicates this attraction to his friends and thereby influences the movement of a whole group. The model uses OpenStreetMap (OSM) data for the underlying map. Routing of users over pedestrian walkways is achieved with the GraphHopper open-source library[2].

Modeling social interconnectivity of clients

The movement model [160] contains four basic steps. First, the *generation and placement of attraction points* is conducted. The placement is either depending on a given strategy, based on OSM data, or provided by a trace. Afterwards, the model *assigns* each mobile client to one attraction point. Our proposed model allows for *i)* a random assignment, *ii)* an assignment to mimic the SLAW movement model [110], and *iii)* the assignment based on social ties taken from social graphs. The target location of assigned attraction points is randomly distributed in the vicinity of the attraction point to prevent clients from targeting the exact same spot. A random offset around the attraction point coordinates (x_0, y_0) is modeled via two Gaussian distributions $\mathcal{N}_u(u_0, \sigma^2) \, \forall \, u \in [x_0, y_0]$. We rely on the default parametrization of the model [160], with a radius r of 25 m and $\sigma = r/3$ resulting in over 98.9 % of the clients being located within r around the attraction point location (x_0, y_0). The *movement of clients towards assigned attraction points* is handled in the third step. We rely on a map-based movement strategy in our work. However, direct linear movement (similar to SLAW [110]) is also supported as a baseline. When a client arrives at the desired attraction point, it waits for a random time t_p, chosen from a uniformly distributed interval $[t_{p,min}, t_{p,max}]$. After waiting for t_p, the assignment to a new attraction point begins. Other than current attraction-based movement models presented in literature, where attraction points are fixed in their location, our model allows for floating attraction points [160]. This floating attraction points can be used to model, e. g., changing points of interest in mobile application such as PokémonGo.

While mobility models such as random waypoint [89] or Gaussian movement [115] are not able to represent human mobility patterns realistically, these models are still widely used in mobile network research [53, 147]. We compare the resulting mobility pattern of the different movement models in the following. Table 3 shows the different mobility models used for the comparison mentioned above and further analysis of the proposed contributions in this thesis.

Representing human mobility

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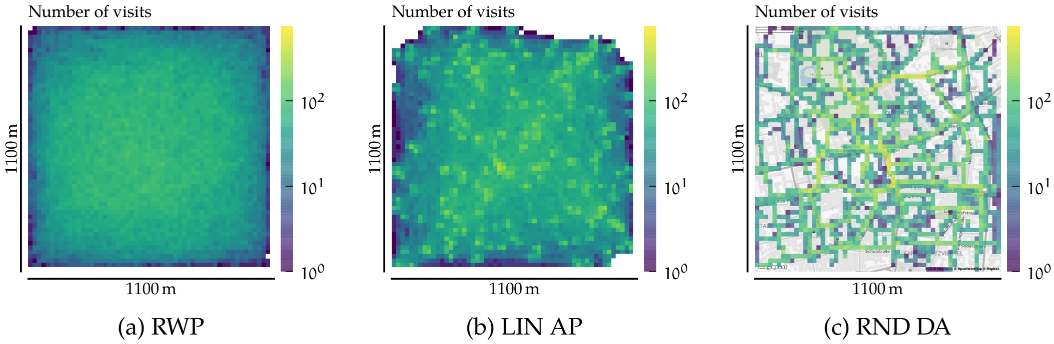
[2] https://github.com/graphhopper/graphhopper, [Accessed December 24th, 2018]

Label	Movement between Positions	Next Targeted Position
RWP [89]	Linear movement without obstacles	Random point on map
LIN AP	Linear movement without obstacles	Random attraction point
RND DA/NY	Map-based via streets and pathways	Random attraction point
DA/NY [160]	Map-based via streets and pathways	Attraction point from Tripadvisor

Table 3: Mobility models used in this thesis. Map-based models use the urban areas of Darmstadt (DA) or New York (NY) for routing of clients via pedestrian walkways.

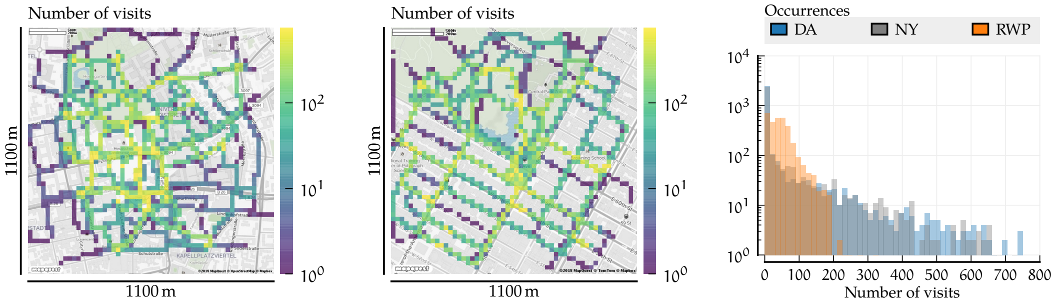


(a) RWP (b) LIN AP (c) RND DA

Figure 21: Number of client visits for the mobility models RWP, LIN APs, and RND DA.

Figure 21 shows the number of visits of the clients during an observation interval of 60 minutes for the different movement models. Visits are measured and aggregated in cells of 20 m × 20 m. The utilized simulation area measures 1100 m × 1100 m. The random waypoint model (see Figure 21a) delivers an even distribution of visits on the simulation area. The model LIN AP uses 200 randomly placed attraction points between which the clients move with linear movement. LIN AP is an evolution of the random waypoint model [89] as it models the movement between static, predefined points of interest, which models human mobility in greater detail as visible in Figure 21b. Still, linear movement of clients and randomly placed attraction points are not representative for human mobility patterns [95]. Map-based movement, as used in Figure 21c, is a significant step towards realistic movement patterns [102]. The model, however, relies on randomly placed attraction points on the urban area, which does not reflect the social points of interests for humans.

Figure 22a and Figure 22b show the two main mobility models used in this work. Both models rely on the movement model, as proposed in [160], with social ties between clients and attraction points, resulting in clients being more or less attracted by different attraction points. Figure 22a shows the model *DA* in an urban area of Darmstadt, Germany, while Figure 22b shows with the model *NY* an urban area in New York, USA. In both models, the social force of attraction points results in more occurrences of clients around those areas. We use locations such as cafés, restaurants, and bars as attraction points as those are meeting places for humans in which they will most likely spend some time before heading for their next destination. We used



(a) DA (b) NY (c) Occurrences on locations

Figure 22: Visualization of the mobility patterns of the DA and NY mobility models [160]. Comparison of the visits of clients on individual locations of the map.

available data from Tripadvisor[3] to decide on socially exciting places for the attraction points on the map. As both models imply different characteristics of the underlying map, we rely on both for our evaluation in this thesis [7]. New York (see Figure 22b) represents a grid-based structure, while Darmstadt (see Figure 22a) is an excellent example for an organic city development often observed in European countries. As the GraphHopper library is more likely to find multiple routes between two locations, the location visits are more equally distributed in grid-based urban structures.

Comparing the influence of city structures

The random waypoint model, as visible in Figure 21a, results in a very homogeneous distribution of clients on the simulated area over time. Realistic mobility models that not only take the social ties between users and attracting points in the urban area into account but also consider the natural movement of humans in urban areas over pedestrian walkways provide a more distributed picture. Figure 22c shows the histogram of the occurrences on the map for the random waypoint model [89] and our used mobility models DA and NY as introduced before (see Table 3). With more client occurrences in the area of attraction points, the interaction times of clients grow naturally as groups of different sizes are formed over time. Figure 22c shows this for both mobility models DA and NY in comparison with RWP. While with RWP places are visited at most 200 times, DA and NY redistribute a large share of the occurrences of the clients to 300 visits and more.

Table 4 summarizes the parameters used for the simulation of the presented mobility models. The movement speed in the simulated 1.21 km^2 area is uniformly distributed between 1.5 $\mathrm{m/s}$ and 2.5 $\mathrm{m/s}$ as suggested and analyzed by Bohannon and Himann et al. in [20, 80]. Movement models that utilize attraction points rely on the pause time of clients t_p, which is selected from the uniformly distributed interval $[10\,\mathrm{s}, 120\,\mathrm{s}]$. Mobile client density varies between 49 and 247 $\mathrm{clients/km^2}$ depending on the utilized churn model. Unless otherwise specified we use a default density of 165 $\mathrm{clients/km^2}$. Additionally, we use fluctuating client densities for later evaluations.

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[3] Tripadvisor is a recommendation website for hotels, restaurants, and other travel-related content. Its reviews and recommendations are mostly user-generated. https://www.tripadvisor.com/, [Accessed December 24th, 2018]

Parameter	Value	Description
Simulation area	$1100\,\text{m} \times 1100\,\text{m}$	Dimensions of the simulated area
Movement speed $[\upsilon_{\text{min}}, \upsilon_{\text{max}}]$	$[1.5\,\text{m}/\text{s}, 2.5\,\text{m}/\text{s}]$	Human movement speed [20, 80]
Pause times $[t_{p,\text{min}}, t_{p,\text{max}}]$	$[10\,\text{s}, 120\,\text{s}]$	Waiting time on attraction points
Mobile client density $\text{clients}/\text{km}^2$	$49 - 247; \underline{165}$	Client density in the simulated area

Table 4: Parameter configuration of the mobility models.

6.1.3 *Workload Model*

In order to evaluate the characteristics and possible advantages or disadvantages of our proposed concept for transitions within monitoring and network offloading, we do not only need to model the dynamics of the mobile environment. The workload on the proposed services is equally important to assess performance characteristics. To limit the impact of external influences in the evaluation, a load generator can imitate workload introduced by various applications. Consequently, the usage of a load generator is a valid substitution for real applications in the simulation and assessment of the characteristics of our proposed contributions.

Workload origin & target clients

We use a model-based workload generator for the evaluation. We differentiate between *origin* and *target* clients. The workload instantiation uses an interval (W_i) to select the origin clients. Filter operations can be expressed as conditions that must be matched by clients in order to act as origin or target clients. Clients that have little battery capacity available are very likely to have a low network activity to save energy and thus create less load. Another example could be a concert, where many people use their device for an adaptive live-streaming of the event. In this case, clients in a particular area introduce a burstier load.

Request invocation

Consequently, we can filter clients based on specific attributes, such as the battery capacity, the location, or the available bandwidth. The filtered set of origin clients is reduced to a maximum size by a trace-based or a mathematical distribution if needed. Information usually is not demanded by all users in the network at the same points in time and intervals. Requests are built according to the introduced design as detailed in Section 5.2. Requests can demand information in a *one-shot*, *periodic*, or *event-based* fashion. For all types the request validity is crucial as outdated information should not burden the network. Similar to the filtering of potential origin clients, requests can contain a set of rules for `SiSTypes` that must be matched by potential target clients. Receiving clients match the rules in the network to determine if the requests targets them and to subsequently send responses to the requesting origin client. Based on the requested `SiSType` also aggregation functions (see Section 5.2) can be instantiated in the workload generator.

Table 5 summarizes the parameter settings used for the workload generator in our evaluations. The origin clients W_O are either selected *i)* from all clients in the network or *ii)* only from gateway clients, selected with AssignMe.KOM (see Chapter 4). Requests are instantiated with an interval of 30 s on the randomly selected clients from

Parameter	Value	Description
Workload origin W_O	$\forall$; $\forall n \in \{C \mid \text{is GW}\}$	Origin are all mobile clients or only on gateways
Interval $[W_{i,min}, W_{i,max}]$	$[30\,s, 75\,s]$	Interval with which requests are instantiated
Request validity R_v	5 min	Time until responses are considered as invalid

Table 5: Parameter configuration of the workload model.

the origin set if not stated otherwise. Requests have a validity of 5 min until responses are considered as invalid in the network. The data that is requested is the location of the clients, assuming a location-based service is requesting location information from a set of clients. Information is required once per instantiated request.

6.1.4 *Network Model*

Infrastructure-assisted or infrastructure-less mobile networks require models for *i)* ad hoc/on-demand local communication between clients and *ii)* interaction of clients with infrastructure entities via their cellular connection. We assume that the cellular network provides reliable connectivity and sufficient bandwidth to the mobile clients until a certain amount of connections $C_{\uparrow\downarrow}$ is exceeded [174]. After exceeding $C_{\uparrow\downarrow}$ the cellular network performance degrades significantly. Table 6 shows the main parameters for the network model. As the focus of this work lays on the local characteristics of the communications, we use a simplified model for the cellular connectivity. Still, this model allows us to examine the essential characteristics of transition-enabled offloading and monitoring in infrastructure-supported networks as proposed with the two main contributions of this thesis. We use a parameter range for $C_{\uparrow\downarrow}$ between $[20\,\%, 70\,\%]$ of the clients. The observable latency of the cellular network $t_{\uparrow\downarrow}$ follows a normal distribution in the interval of $[50\,ms, 250\,ms]$, to model 3G and 4G connections under different load conditions.

For on-demand local communication between clients, we require a more detailed model. We use the 802.11g model from the ns-3 network simulator [79] for Wi-Fi communication. This model is already integrated into the PeerfactSim.KOM platform [151]. We configured the logarithmic propagation loss model with a loss exponent of 3.8, which results in a maximum communication range of the Wi-Fi signals of $r_{\text{Wi-Fi,max}} = 88\,m$ (as visible in Table 6). This range is similar to the observations of Wi-Fi signal strengths in urban areas made in [21, 120]. We model errors for the orthogonal frequency-division multiplexing with the NIST error rate model, also taken from the ns-3 network simulator [79]. By exchanging RTS and CTS messages, this model also allows for unicast transmission between two clients. With this configuration the 802.11g model determines a simulated noise floor to assess the probability of collisions. Besides the maximum communication range of $r_{\text{Wi-Fi,max}} = 88\,m$, the loss exponent of 3.8 increases the potential for collisions within a range of up to 205 m. The effects of different client densities and simultaneous transmissions of adjacent clients are observable with this model for the shared communication means. For our contribution

Parameter	Value	Description
Cellular connectivity $C_{\uparrow\downarrow}$	[20 %, 70 %]; <u>35 %</u>	Reliable service for X % of the clients [174]
Cellular network latency $t_{\uparrow\downarrow}$	150 ms ± 100 ms	Normal distributed cellular network latency
Wi-Fi model	802.11g	Used ns-3 Wi-Fi model [79]
Path loss exponent α	3.8	Path loss in urban areas [21, 120]
Wi-Fi range $r_{\text{Wi-Fi,max}}$	88 m	Resulting from Wi-Fi loss exponent of 3.8

Table 6: Parameter configuration of the network models.

of transition-enabled mobile network monitoring and offloading, this model allows us to represent the fundamental characteristics of dynamic mobile environments.

6.1.5 *Evaluation Metrics*

For the evaluation of our two proposed contributions, we rely on a set of metrics to assess their performance under dynamic conditions. This set of metrics is introduced and explained in the following. We measure most of the metrics presented in the following for both requests and responses.

RECALL The recall describes the proportion of the number of relevant objects retrieved from a set of objects based on a defined inquiry [185]. Thus, the recall describes how many of the relevant objects are selected or retrieved.

PRECISION The precision shows how many of the retrieved objects are relevant to the inquiry. It can be used to determine how large the overhead of a request distributing procedure is, considering requests that do not target all clients in the network.

LATENCY We use the latency of the request distribution and response collection procedure in this work. Thereby, we differentiate between different intermediate and end points for the latency, such as request-till-response or request-to-responders.

ROLE RATIO For both of our contributions, the ratio of roles is an important metric to determine the load on individual clients and the fairness among clients.

TRAFFIC We collect traffic related data for both the cellular and the local on-demand traffic, to assess the overhead of different approaches and the overall load that is introduced in the network.

For the combined usage of our contributions on the exemplary scenario of location-based services, we rely on the following additional metrics. The *position offset* describes the distance between the true and the estimated position of a client. This metric is taken directly after the computations for the estimations are finished. Additionally, we measure the *offset over time* sampled every 5 s to assess the impact of longer measurement intervals and the movement of clients. Both offset metrics are used to assess the accuracy of the approach. We use the measurement state ratios of the sensor on clients to assess the introduced cost for the location retrieval. This abstract cost metric has the advantage that it is independent but compatible with specific cost models, still providing the same insights to the introduced costs. The used measurement states describe the life cycle phase of localization sensors (e. g., GPS), which are *activation*, *continuous measurement*, *deactivation*, and *no measurement*. We use the measurement state as a combination of the activation and continuous life cycle states because these introduce costs at the clients. We observe the ratios of the measurement states because the overall number of states does only change with the measurement interval.

Fairness Measures in Communication Networks

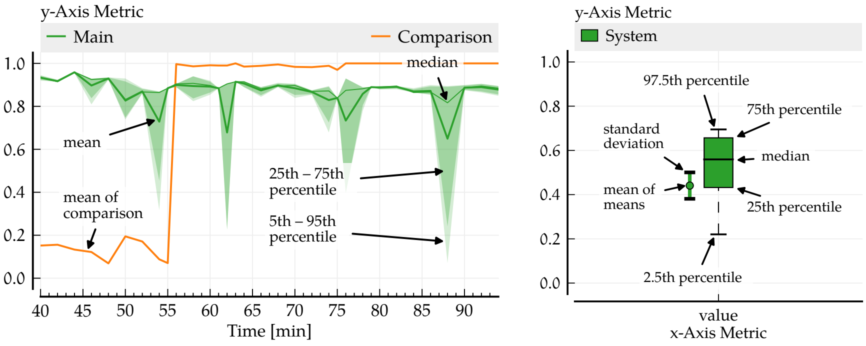
According to Shi et al. [176], fairness is an *"interdisciplinary research topic which is usually related to resource allocation"* and that it is often interconnected with performance studies. Unfair resource allocation in the domain of mobile networks can cause *"resource starvation, wastage, or redundant allocation"* at worst [161, 176]. To assess fairness in a mobile scenario *i)* a definition of fairness, *ii)* a method to measure system fairness for individuals and the whole system, and *iii)* an answer how a system can be designed to operate in a fair fashion are required. According to Jain et al. [88], fairness in a distributed system expresses the level of equality of resource distribution among the users. The authors observed that, from the literature, there is no consensus on which resources should be allocated equally. Therefore, Jain et al. believe that rating fairness of a system requires an appropriate allocation metric, as well as a formula that describes the fairness of the allocation by assigning it a quantitative value.

There exist *qualitative* and *quantitative* measures for computing the fair allocation of resources in the literature which we discuss in the following. Qualitative fairness measures as found in [19, 99, 127, 142] do not assign a bound numerical value that describes the fairness level. The lack of such a numerical value aggravates the process of comparing different fairness levels. Thus, also according to Jain et al. [88], to allow for comparison, we rely on quantitative fairness measures in this thesis. The *min-max ratio* [137] has the advantage of not being affected by scale. It only takes the outer most values into account, which does not give a thorough overview of the system's fairness. The *variance* s^2 is a measure for the distribution of data and assists in finding single outliers. It is defined as shown in Equation 7.

$$s^2 = \frac{1}{k} \cdot \sum_{i=1}^{k} (x_i - \overline{x})^2 \tag{7}$$

Here, k is the number of observed values, $x_1, ..., x_k$ are the actual observed values, and $\overline{x}$ is the arithmetic average of the observed values. Because the variance is not independent of scale, the relative variance $s^2/\overline{x}$ can be used instead. Cumulative distribution functions are used to identify the impact of outliers, i. e. unfairly treated single clients, instead of the relative variance, as they show the valuable information about the distribution of a metric [44].

JAIN'S FAIRNESS INDEX The fairness index $FI(x)$ as defined by Jain [88] is independent of scale and can be applied to any resource-allocation, or resource-sharing



(a) Time plot (b) Box plot

Figure 23: Main plot types used in the evaluation.

system. In Equation 8 the index is detailed. n describes the number of users in the system of which each i^{th} user receives an allocation x_i of any kind of resource [88].

$$FI(x) = \frac{(\sum_{i=1}^{n} x_i)^2}{n \cdot \sum_{i=1}^{n} {x_i}^2} \tag{8}$$

$FI(x)$ ranges between 0 and 1, while a value close to 0 reports a low fairness in the system, a result of favoring or burdening only a few users. Values between zero and one detail the percentage of the analyzed system's fairness. $FI(x)$ does not imply to which extent users get or consume a resource. Thus, whenever quantitative fairness metrics are used, the total value of the shared resource must also be taken into account.

We rely on Jain's fairness index $FI(x)$ in this work to estimate the fairness characteristics of our contributions.

Plot Types

Figure 23 details the main plot types used in the following. Time plots as visible in Figure 23a consist of *main* and *comparison* systems. For main systems, the mean (bold line), median (thin line), the $25th - 75th$ and the $5th - 95th$ percentiles are shown. Comparison systems show the mean over all seeds.

Box plots show the distribution of the results as visible in Figure 23b. The solid line inside the box represents the median. The lower and upper quartiles are represented by the lower and upper end of the box. Whiskers show the lower and upper data point within 1.5 of the interquartile range. As box plots show the results of a single simulation run, a dot with error bars is plotted to the left side of the boxes indicating the mean of the means and the standard deviation for the former over all repetitions with different random seeds. For the simulation runs in the evaluation we relied on 30 randomly selected seeds.

Mechanism	Description
C/S	Centralized client-server monitoring.
H-PROB	Hybrid with local ad hoc probabilistic communication.
H-DIR	Hybrid with local ad hoc bio-inspired communication.
H-DTN	Hybrid with local communication based on DTNs.
BFLO	Decentralized simple buffered flooding.
EPI	Decentralized epidemic.

Table 7: Monitoring mechanisms used in the evaluation.

6.2 TRANSITIONS IN A MONITORING SERVICE FOR MOBILE NETWORKS

Characteristics of static monitoring mechanisms

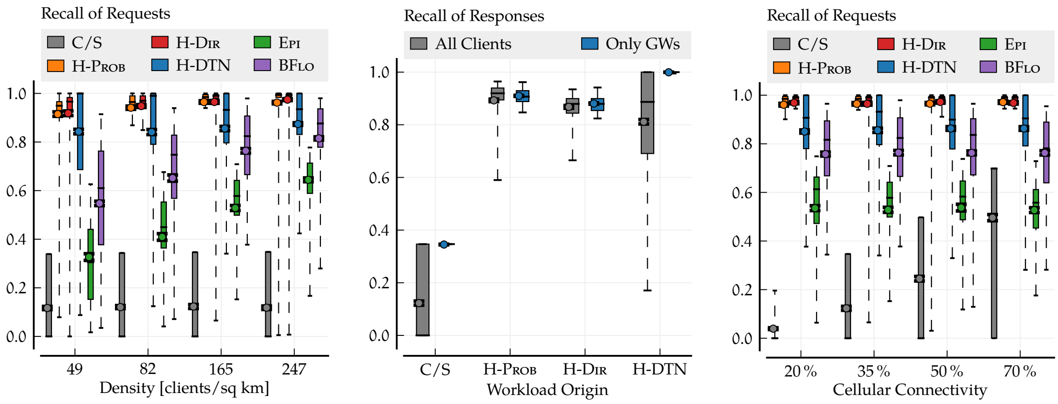
To understand the characteristics of individual monitoring configurations we observe the mechanisms in different static environments. We use the monitoring mechanisms as detailed in Table 7 for the evaluation. The mechanism C/S only uses cellular communication. Thus, only clients with a cellular connection can be monitored. The three hybrid mechanisms H-PROB, H-DIR, and H-DTN use assigned gateways for cellular communication in combination with different local communication strategies. H-PROB uses ad hoc probabilistic flooding to disseminate and collect data in the mobile network. We use a bio-inspired communication scheme for the collection of responses and probabilistic distribution of requests in H-DIR [162]. H-DTN combines gateway-based cellular communication with periodic buffered flooding. The decentralized mechanism BFLO relies on a buffered flooding approach, while EPI tries to reduce the overall overhead by exchanging content based on a negotiation protocol.

Figure 24a shows the recall of requests under different densities. The density of environments is mainly influencing the decentralized monitoring mechanisms. Hybrid mechanisms are also impacted but can use assigned gateways to route traffic via cellular communication to less dense areas. The decentralized mechanism EPI is not able to cope with less dense populations compared to BFLO. The longer advertising interval of the known monitoring data in EPI and fewer encounters are the reason for the drop in achieved recall.

. . . in constant environments.

In overload environments with different cellular connectivity characteristics only the mechanism C/S shows a strong dependency on $C_{\uparrow\downarrow}$. Figure 24c shows the recall of requests under different $C_{\uparrow\downarrow}$. When a request is potentially originated on any client in the network it is very likely that the currently connected clients in C/S are not selected as originating client. Consequently, a large part of the requests is lost after invocation.

The origin of the workload W_O (see Section 6.1.3) has a strong influence on the centralized and hybrid monitoring mechanisms as visible in Figure 24b. We can see that the response recall of the mechanisms increases once requests are originated on gateways. This is reasoned in the shorter path from the responder to the requester as the requester remains in the gateway role most likely in the time the responses are collected, which saves the dissemination of responses in the local network in most cases. Furthermore, requests are more likely to arrive at the targeted clients, which is



(a) Recall of requests (Density) (b) Recall of responses (Origin) (c) Recall of requests (Connectivity)

Figure 24: Recall of the monitoring mechanisms under different environmental conditions in the DA scenario.

also decreasing the time from request invocation till response reception as visible in Appendix A.1.

We can observe that the structure of AdaptMon.KOM allows for the instantiation of various static monitoring mechanisms for comparison and an in-depth evaluation of their individual characteristics. Due to space constraints, additional results for the evaluation of static monitoring approaches are presented in Appendix A.1. Additionally, *i)* the originating client, where the request is invoked, has a significant impact on the achieved recall and *ii)* a combination of gateway-based cellular communication and local collection and dissemination based on DTNs reduce the potential of lost monitoring data.

6.2.1 *Dynamic Environments and Static Monitoring*

From now on, we focus on the impact of dynamic environments on static monitoring mechanisms and the transition-enabled monitoring service AdaptMon.KOM. To assess the impact of transitions and the performance of the static monitoring mechanism in dynamic environments we rely on two different scenarios as explained in Table 8. For that purpose, we use the mobility environments of DA and NY (see Table 3). The overload scenario models a network in a normal operation state with an increasing client density over time. Similar to the observation made by Shafiq et al. [174], we assume that the infrastructure-based network service degrades significantly after exceeding a certain threshold of connections requests. The client density in the overload scenario increases from 49 to 165 clients/km^2 between minutes 50 and 54. With 165 clients/km^2 the cellular network is only able to service 30 % of the clients. A second increase in the client density between minutes 70 and 75 to 206 clients/km^2 leads to the cellular network failure around minute 75. The second scenario models a network recovery after a breakdown or power outage. We assume the infrastructure-based net-

. . . in dynamic environments.

Label	Description
Overload	**Modeling of an overload scenario, which leads to network failure.** Increasing client density over time. With a growing number of cellular connection requests [174], originated by more clients, a network breakdown is observable. AdaptMon.KOM configured with transitions from C/S $\xrightarrow{T1}$ H-Prob $\xrightarrow{T2}$ Epi
Recovery	**Modeling of a recovery scenario, in which the infrastructure-based network slowly resumes the service.** We use a constant client density over time to concentrate on the impact of the regaining cellular network coverage. AdaptMon.KOM configured with transitions from Epi $\xrightarrow{T1}$ H-Prob $\xrightarrow{T2}$ C/S

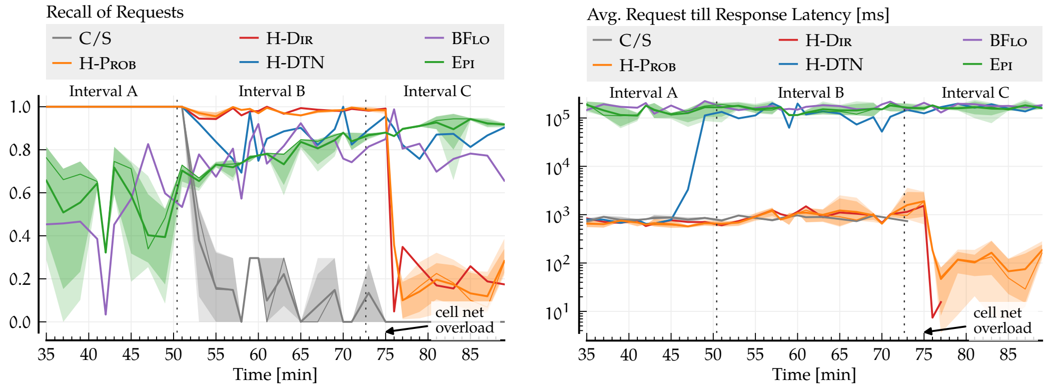
Table 8: Scenarios for fluctuating environments used to assess the impact on statically configured monitoring mechanisms and AdaptMon.KOM.

Overload & recovery scenarios

work to slowly resume its service. Unlike the first scenario, the client density remains constant in the recovery scenario. Around minute 50 the cellular network resumes its service for up to 50 % of the clients. Later, around minute 70 the cellular network can service all mobile clients in the considered area. For the discussion we split both scenarios in the intervals A, B, and C, which denote the times between environmental changes. The two scenarios are similar to what is observable in post- and pre-disaster network conditions [130] but are reduced to the essential.

Limited applicability of static monitoring mechanisms

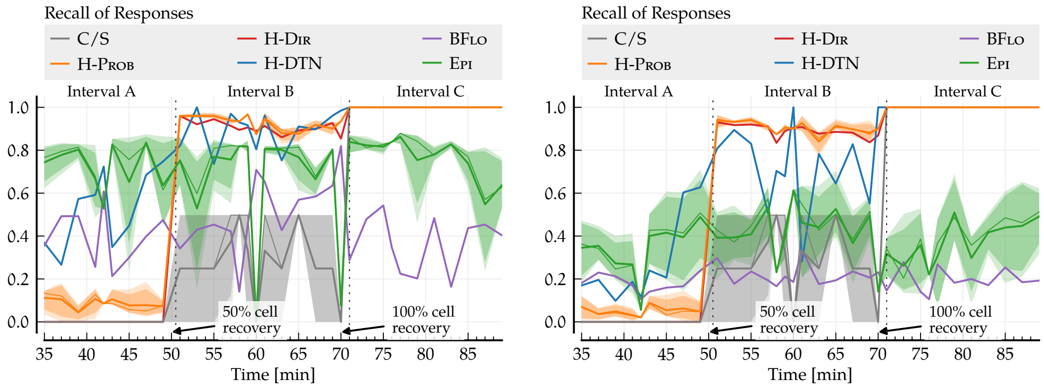
We first consider the static monitoring mechanisms (see Table 7) in the dynamic scenarios explained before. Figure 25 shows recall of requests and the latency from request invocation till response reception in the overload scenario with the DA movement model. It is visible that the individual mechanisms perform best in the environmental range these mechanisms were designed for. This matches with our evaluation results considering the characteristics of the monitoring mechanisms in non-changing environments. The recall of the requests, visible in Figure 25a, details that C/S and the hybrid approaches perform best in Interval A. C/S cannot uphold the recall in



(a) Recall of requests over time

(b) Latency of responses over time

Figure 25: Impact of the overload scenario on the monitoring mechanisms with the DA movement model.



(a) Recall of responses over time (DA)

(b) Recall of responses over time (NY)

Figure 26: Recall of responses in the recovery scenario with the DA and NY movement model.

Interval B, as at best only 30 % of the clients can answer the requests and additionally non-connected clients can be chosen as the workload origin W_O. Both decentralized approaches Epi and BFlo benefit from the increased density. After the cellular network overload, the infrastructure-assisted monitoring mechanisms C/S, H-Dir, and H-Prob show their strong dependency on the cellular network. The mechanisms H-Dtn, Epi, and BFlo can deliver the monitoring data in the infrastructure-less network in Interval C. As a consequence, the latency from request invocation till response reception increases significantly shown in Figure 25b. The decreasing latency for H-Prob and H-Dir in Interval C is caused by the fact that both approaches use direct ad hoc communication between adjacent clients. Requests and responses are only exchanged in a small area around the originating client but in a short period. The sharp decrease of the recall of requests in Interval C (see Figure 25a) shows this similar to the decrease of delivered responses as shown in Appendix A.1. The achieved recall of the responses behaves similarly to the recall of requests shown in Figure 25a.

Figure 26 shows the recall of the responses for the recovery scenario using the two different underlying map models of DA and NY. It becomes apparent that the higher number of possible routes, justified by the grid structure of the NY map Section 6.1.2, leads to less encounters of the clients during the change from one attraction point to another. As a result, the recall of the decentralized monitoring mechanisms BFlo and Epi with the NY movement model Figure 26b is lower compared to DA shown in Figure 26a. We can see that the static monitoring mechanisms *i)* differ in the achieved performances concerning the dynamic environment of the overload and recovery scenario and that *ii)* the mechanisms are not able to provide a consistent monitoring quality over time due to their limited adaptability. This motivates the need for transition-enabled systems such as AdaptMon.KOM. The ability to execute transitions between different monitoring mechanisms during operation would enable a significant increase in the monitoring quality over time.

Need for adaptivity within monitoring

6.2.2 *Transition Execution and Coordination in Dynamic Environments*

Potential of transition-enabled monitoring

We use AdaptMon.KOM with two different configurations to assess the characteristics of the transition-enabled monitoring service. According to the scenarios introduced in Table 8, we plan the following transitions in the network. For the overload scenario AdaptMon.KOM is configured as C/S monitoring approach. In between Interval A and B we execute a transition from C/S $\overset{T1}{\rightarrow}$ H-Prob. With the last increment of the client density (in between Interval B and C) AdaptMon.KOM executes a transition between H-Prob $\overset{T2}{\rightarrow}$ Epi. In the recovery scenario AdaptMon.KOM is configured as Epi monitoring approach. With the cellular network service recovering for 50 % in time Interval B, we execute the transition from Epi $\overset{T1}{\rightarrow}$ H-Prob. Later in between time Interval B and C, the cellular network can service all mobile clients in the considered area, AdaptMon.KOM transitions from H-Prob $\overset{T2}{\rightarrow}$ C/S. For both scenarios, each transition is triggered on a random client in the network. The transitions are modeled based on the results of the evaluation of static monitoring mechanisms. As we do not focus on the question of when and why transition should be executed at best, we rely on pre-defined transition plans. This allows us to focus on the impact of transition coordination mechanisms. We rely on three different transition coordination mechanisms, which are explained in the following.

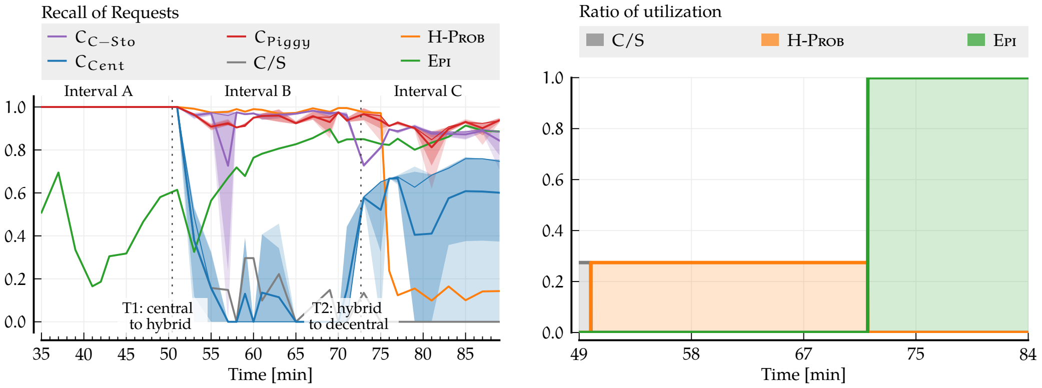
C_{Cent} Transitions are delivered to all affected clients using individual messages in the cellular network. The originating client uploads the transition plan to the cloud, where it is distributed to all affected clients. The approach is not relying on buffering of transition execution plans. Thus, if clients are not online to receive the transition plan, they will not execute the transition.

$C_{\text{C-Sto}}$ Similar to C_{Cent} this mechanism relies on individual messages distributed using the cellular network to notify clients on transition plans. However, this approach buffers all transitions and informs clients that join the network and register with the central coordination entity on the transitions executed in the past. This allows joining clients to adapt to the current configuration in the network.

C_{Piggy} Transition plans are attached to all messages sent out in the network. Thus, to distribute transition plans, this mechanism solely relies on messages sent in the network anyways. Each client adds its known transition plans to any messages sent out. Receiving clients synchronize the received knowledge with their own and adapt to potential newer configurations. Originating clients use a time-limited periodic broadcast to improve the spreading of transitions.

Transition coordination mechanisms

For the distribution of the transition execution plans with C_{Cent} and $C_{\text{C-Sto}}$ in the cellular network, we assume that those small payload messages can also be distributed in cases of network overload [174]. We assume this to allow for the comparison of the coordinators in the two scenarios depicted before. We compare the transition-enabled configuration of AdaptMon.KOM per scenario (see Table 8) with the respective static monitoring approaches C/S, H-Prob, and Epi.



(a) Recall of requests over time

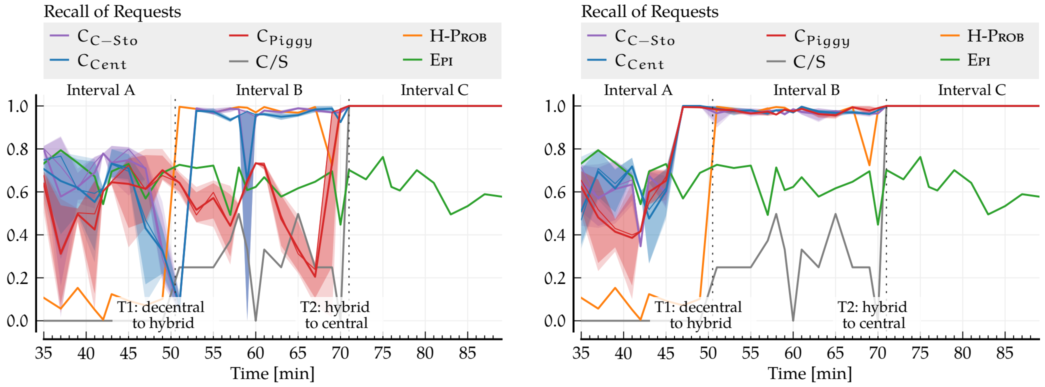
(b) Mechanism utilization with C_{Cent}

Figure 27: Comparison of AdaptMon.KOM and static monitoring mechanisms in the overload scenario with the DA movement model.

Transition coordination in the overload scenario

In Figure 27 we report the recall of requests and the mechanism configuration of the clients with C_{Cent} in the overload scenario with the DA movement model. In this setup the inter-proxy state transfer as introduced with AdaptMon.KOM in Section 5.4 is disabled. The delivery success of requests in AdaptMon.KOM using the transition coordinator configurations $C_{\text{C-Sto}}$ and C_{Piggy} shows that the system successfully performs the transition between the monitoring mechanisms C/S and H-Prob (see Figure 27a). In the C_{Cent} configuration, clients joining the network after the first transition do not receive this information. Accordingly, the clients remain in the default state of AdaptMon.KOM and perform no monitoring. This behavior is again visible for the second transition, where all online clients receive the information to execute the transition to Epi as visible in Figure 27b. This explains the sharp drop in the achieved recall for C_{Cent} visible after the first transition in Figure 27a. All three transition coordinators can execute the second transition from H-Prob to Epi reliably. After a short start-up phase AdaptMon.KOM provides similar results as the static configured mechanism Epi. The drop in the achieved recall after executing the transition to Epi is reasoned with the filling of buffers of the Epi mechanism. Once the clients' knowledge on monitoring information increases, the sharing process in Epi regains its full potential, leading to a similar performance of the transition-enabled monitoring service compared to the continuously running Epi mechanism. The monitoring process with AdaptMon.KOM adds minimal overhead in the network as discussed in Appendix A.1.

Clients download at most $8\,{}^{\text{kbit}}/_{\text{s}}$ monitoring data from the cloud, while the total cellular upload is below $50\,{}^{\text{kbit}}/_{\text{s}}$ for both the DA and NY movement setting in the overload scenario. $75\,\%$ of the clients have cellular download rates below $1\,{}^{\text{kbit}}/_{\text{s}}$. The impact of the grid-based structure of NY on local communication, as identified in Figure 26, becomes again evident in Appendix A.1. We show additional spreading analysis results of this configuration in Appendix A.1.



(a) Without inter-proxy state transfer

(b) With inter-proxy state transfer

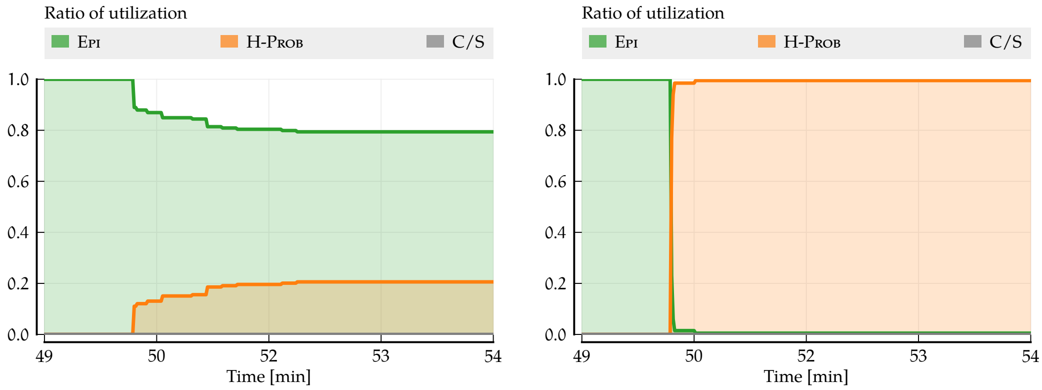
Figure 28: Impact of inter-proxy state transfer in the recovery scenario with the NY movement model. Transitions T1: Epi $\xrightarrow{T1}$ H-Prob and T2: H-Prob $\xrightarrow{T2}$ C/S.

6.2.3 *Transitions with Inter-proxy State Transfer*

Recovery scenario: Inter-proxy state transfer

. . . for seamless operation

In the following, we consider the recovery scenario with and without the usage if inter-proxy state transfer during transitions. As detailed in Section 5.4, state can either be transfered between two strategies used in one proxy (intra-proxy) [67, 148] or, as proposed in this work, between two proxies in a transition plan (inter-proxy). In this scenario transition T1 switches between Epi and H-Prob, while T2 switches between H-Prob and C/S. Thus, the potential of inter-proxy state transfer can be analyzed for transition T1 as the monitoring mechanism Epi stores all received requests and responses. Figure 28 shows the recall of the requests over time for the recovery scenario with the NY movement model with and without inter-proxy state transfer. Without inter-proxy state transfer, the achieved recall of requests experiences a sharp drop with transition T1 between Epi and H-Prob. This drop of the recall becomes apparent in Figure 28a for C$_{\text{Cent}}$ and C$_{\text{C-Sto}}$. The transition plan is not executed reliably with C$_{\text{Piggy}}$ as shown in Figure 29a, thus AdaptMon.KOM remains in the Epi configuration, which explains the behavior visible in Figure 28a. The few clients that execute the transition with C$_{\text{Piggy}}$ once T1 is executed for the first time are the clients in direct proximity to the initiating client. The drop in the recall of requests for C$_{\text{Cent}}$ and C$_{\text{C-Sto}}$ is reasoned in the loss of all data of all active requests and a more extended period of potential incompatibility between Epi and H-Prob due to a delayed transition execution for requests invoked shortly after the transition. Considering the same scenario, but with enabled inter-proxy state transfer, we can see that the transition is executed smoothly, with the system switching from Epi to H-Prob seamlessly (see Figure 28b). The recall of already active requests is improved significantly, as with T1 the cellular infrastructure is used in addition to the local probabilistic distribution of H-Prob to distribute monitoring data in the network. C$_{\text{Piggy}}$ executes reliably on all clients, with very low delay.



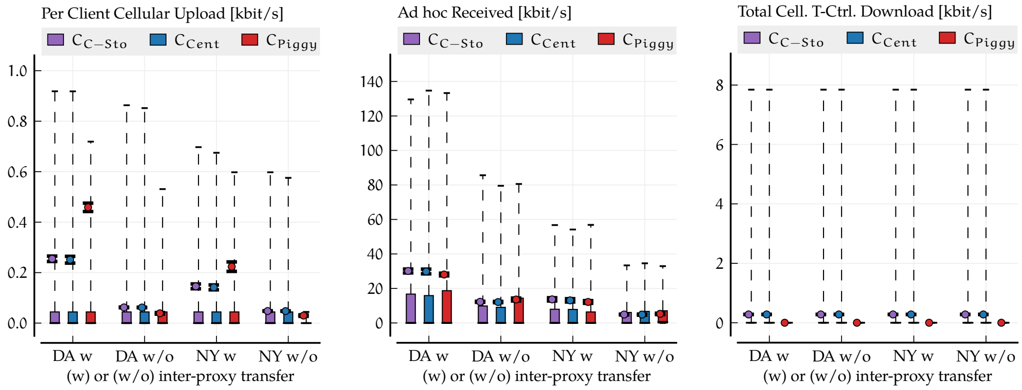
(a) Without inter-proxy state transfer

(b) With inter-proxy state transfer

Figure 29: Comparison of the transition spreading (recovery scenario and NY movement model) for T1: Epi $\xrightarrow{T1}$ H-Prob with the transition coordinator C_{Piggy}.

Not only the performance of the system is improving due to inter-proxy state transfer. Transitions are executed faster and more reliable as the additionally transferred state results in increased communication after the transition. We show this effect for transition T1 (Epi to H-Prob) with the C_{Piggy} in Figure 29. Without inter-proxy state transfer, especially the uploading proxies of the monitoring mechanism H-Prob are not retrieving information from other previously active local dissemination proxies in the Epi configuration of AdaptMon.KOM. Without this information from the previously active proxies the hybrid monitoring mechanism H-Prob will not start communication until new requests are invoked. Thus, with less or no available information the piggybacked transition plan is spread slower, which is visible in Figure 29a. Only when a client that already executed transition T1 invokes a request, the transition spreads in the network with C_{Piggy}. Using our proposed inter-proxy state transfer not only reduces the potential for information loss, but it also has the potential to reduce the execution delay of transition decisions in the network as visible in Figure 29b. The additional information that is shared during transition T1 using inter-proxy state transfer leads to a direct exchange of monitoring data in the network within H-Prob. Thus, not only the recall of the monitoring data is improved significantly (see Figure 28b) also the transition is executed more reliable. This becomes highly relevant in the domain of network monitoring services. Compared to systems such as video streaming [167, 199, 201] or publish/subscribe [148, 150], where high network utilization and client connectivity with a centralized entity is very likely, monitoring services such as AdaptMon.KOM are seen as low overhead background services [171]. The constant inclusion of all clients in the network with high frequencies is unlikely in such background services, which poses additional challenges for the distribution of transition decisions in the network. As visible in Figure 28a the usage of C_{Piggy} without inter-proxy state transfer for transition coordination results in a reduced performance due to the longer execution times for the transition plan in the network.

. . . faster transition spreading



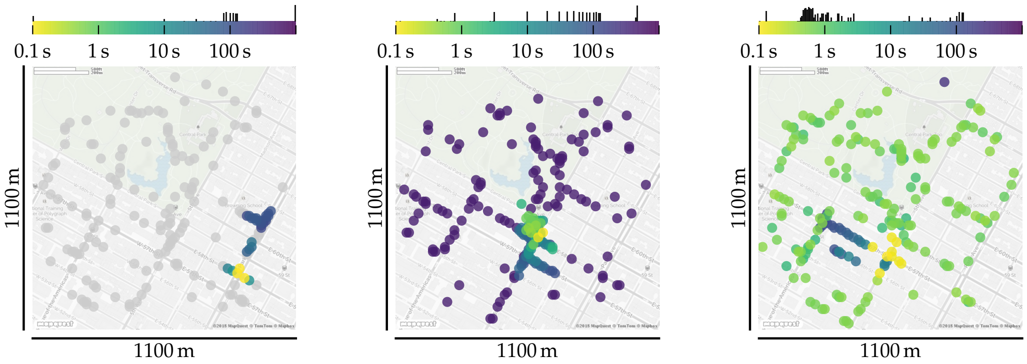
(a) Per client cellular upload (b) Ad hoc received (c) Transition control download

Figure 30: Cellular monitoring, ad hoc monitoring, and transition coordination traffic in the recovery scenario.

In Figure 30 the traffic in the recovery scenario for both DA and NY movement settings with and without inter-proxy state transfer is shown. The cellular upload of monitoring data per client (see Figure 30a) and the ad hoc received monitoring data shown in Figure 30b reveal that AdaptMon.KOM achieves complete monitoring of the network with low overhead. Comparing the DA and NY environments for both, the cellular and ad hoc traffic, we can see that higher traffic occurrences are likely in the DA environment. The skew indicated by the size of the box in Figure 30b is nearly twice as large as for the NY environment. This is reasoned in more loss of monitoring data in the NY environment due to fewer client encounters in the grid-based urban area, where clients are more likely to choose different paths to the same destination. Inter-proxy state transfer does not only improve the reliability of the transition execution and the resulting system performance as shown before. As all stored requests and responses are transferred from Epi to H-Prob during transition T1, the ad hoc traffic is also increasing which is shown in the box and whisker ranges in Figure 30b and the increasing mean of means. The total download overhead for transition coordination as shown in Figure 30c is minimal in comparison to the monitoring data traffic. The whiskers of the boxes show the transition coordination traffic during the executions of the transition plans. With two transition plans in the simulation period, the coordination traffic is zero for most of the observation time. We see that both, C_{Cent} and $C_{C\text{-}Sto}$ introduce similar overhead, while C_{Piggy} allows for transitions without significant additional overhead in the cellular network as transition coordination information are piggybacked on messages sent anyway.

Low overhead of monitoring & transition coordination

In Figure 31 we can see the resulting transition spread with C_{Piggy} for transition T1: Epi $\xrightarrow{T1}$ H-Prob with and without inter-proxy state transfer. Transition spread plots show the underlying map and the locations of the clients when they executed the transition. Additionally, the coloring of the execution locations shows the latency with which the transition has been executed after the first occurrence of the transition in the network. On top of the plot a histogram is used to aide in understanding the



(a) Without state transfer (b) Without state transfer (c) With state transfer

Figure 31: Transition spread for T1: EPI $\xrightarrow{T1}$ H-PROB in the NY recovery scenario with C_{Piggy}. With and without inter-proxy state transfer.

distribution of the transition execution latency on the clients. Figure 31a and Figure 31b show the transition spread of T1 for two different seeds without inter-proxy state transfer in AdaptMon.KOM. The figures show the previously discussed problem that without information transfer from the previously active proxies the hybrid monitoring mechanism H-Prob will not start communication until new requests are invoked. Thus the transition will not spread until one of the already transitioning clients invokes a request. Depending on the network, this can happen faster or slower and might result in some clients never receiving the transition decision. Nevertheless, as the monitoring service is most likely used in combination with utility systems where high network utilization and client connectivity with a centralized entity is likely, transition decisions will spread better with C_{Piggy} in these scenarios. However, as this is not guaranteed the monitoring service itself must ensure a network-wide spreading of transition decisions. With inter-proxy state transfer and the low overhead coordinator C_{Piggy}, the transition spreads within 100 s in the whole network as visible in Figure 31c.

The results obtained in the overload scenario, but with enabled inter-proxy state transfer, do not change as both monitoring mechanisms C/S and H-Prob do not buffer any monitoring data for possible inter-proxy state transfer. Thus, no monitoring data is exchanged during the execution of both transition plans for transitions T1 and T2.

Seamless operation in dynamic environments

In summary, the evaluation results of AdaptMon.KOM show that individual monitoring mechanisms perform superior in the intended conditions. However, in dynamic environments, the static monitoring mechanisms cannot provide for seamless operation. Our proposed transition-enabled monitoring service AdaptMon.KOM depicts the functionality of single individual monitoring mechanisms by separating and encapsulating the mechanisms and functional components. In doing so AdaptMon.KOM provides for a multitude of potential configuration choices applicable under a wide range of environmental conditions. We showed the usage of the transition concept within mobile network monitoring in two scenarios, depicting an overload and a recovery situation in a network. The achieved monitoring performance depends strongly on *i)* the point (client location, connectivity) where the transition decision is made and *ii)* the transition coordination process, which we analyzed relying on the transition coordinators C_{Cent}, $C_{\text{C-Sto}}$, and C_{Piggy}. The introduced extension of the state transfer for inter-proxy functionality is, if applicable, an essential concept within the execution of transition plans in environments with coexisting multi-mechanisms. Inter-proxy state transfer allows for seamless operation even if proxies are switched to a non-operational status as data is shared among the stopping and starting proxies within a transition plan. Furthermore, this warm start allows for faster transition spreading relying on piggybacking transition coordinators as C_{Piggy}. For background services such as network monitoring, this is essential as it allows for transition spreading without causing additional overhead due to dedicated messages in the network.

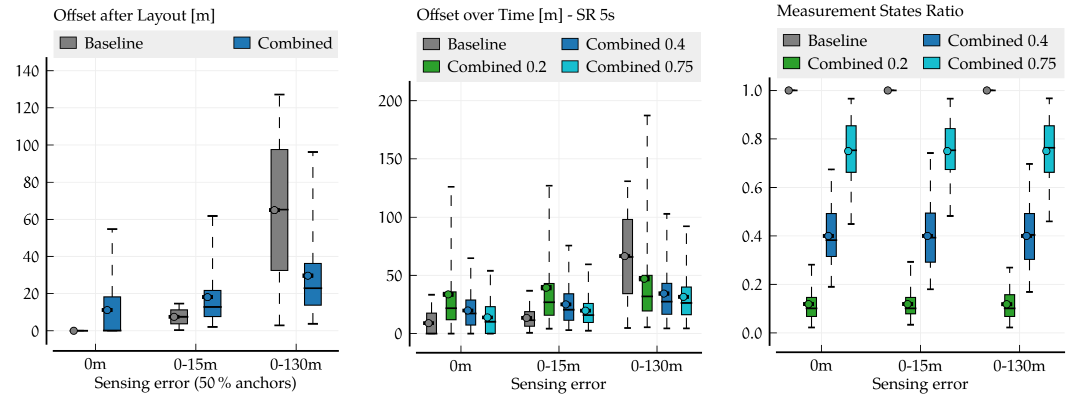
6.3 COMBINED USE OF COEXISTING TRANSITION-ENABLED MECHANISMS

The usage of only a single multi-mechanism in future networking scenarios is highly unlikely. The combined usage of transition-enabled mechanisms can entail many advantages, but also shows the dependencies of the dynamic mechanisms. We focus on the combined usage of AssignMe.KOM and AdaptMon.KOM for the exemplary use case of location-based services (see Section 5.5) and discuss the resulting dependencies of both mechanisms throughout the analysis. The results are based on our work presented in [153]. For monitoring of the required data, we rely on AdaptMon.KOM in the H-Prob configuration. The selection of anchor clients, i. e. those clients that perform the location measurement, is achieved with AssignMe.KOM. We configured both transition-enabled services with the best suited mechanisms for the considered scenario to assess the achievable location estimation accuracy of our approach.

De facto standard in localization

We compare our combined solution with the de facto standard in location-based services, which is to rely on measurements conducted by all clients—often using the accurate but cost-intensive GPS localization technique. With that we analyze the combination of the achieved *i)* position accuracy, *ii)* cost-awareness, and *iii)* fair usage of resources for localization in mobile networks. We use three different models to include the effect of sensing errors, depending on the localization techniques (e. g., GPS or Wi-Fi triangulation) [204]: *i)* the no-error sensing model $\varepsilon_{0\text{m}}$, *ii)* the GPS-assisted error between zero and 15 m ($\varepsilon_{0-15\text{m}}$), and *iii)* the Wi-Fi error between zero and 130 m ($\varepsilon_{0-130\text{m}}$). The sensing errors follow a circular error probability with its radius set to $\varepsilon/2$. A detailed parameter study of the mechanisms for the use case of a location-based service is presented in Appendix A.3.

Figure 32 shows the performance and cost comparison of the combined use of our two main contributions with the baseline approach. In a configuration with only 50 % of the clients as anchors, our combined approach achieves offsets below 22 m for 75 % of the clients (see Figure 32a). However, the GPS baseline approach is 10 m more accurate but introduces twice as much costs as each time all clients have to estimate their positions using the GPS sensor. Considering the Wi-Fi-assisted localization baseline, which is significantly less cost-intensive compared to the GPS baseline [204], the



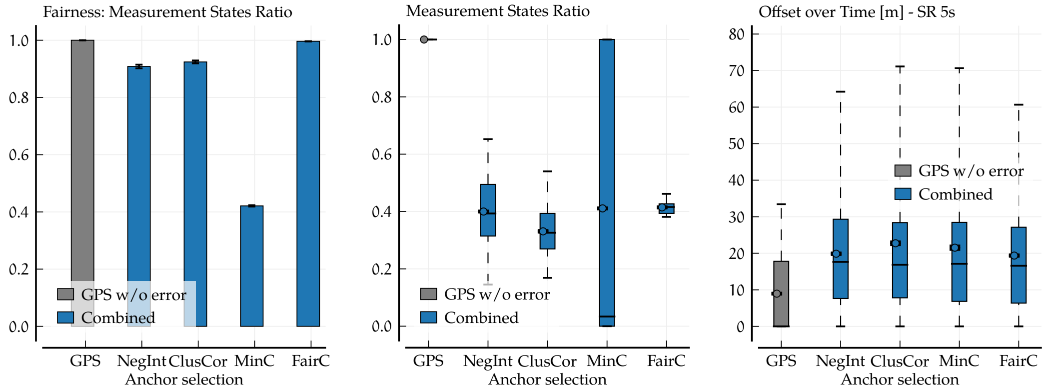
(a) Offset after layout (b) Avg. offset over time (c) Ratio of cost states

Figure 32: Performance and cost comparison of the combined use of AssignMe.KOM and AdaptMon.KOM for localization compared to the baseline approach with either GPS- or Wi-Fi-assisted position sensing.

location error is $\varepsilon_{0-130\text{m}}$. Such localization techniques often find no application as the achieved position accuracy is not meeting required standards. Figure 32a shows that with 50 % of the clients as anchors, the combined approach achieves an improved accuracy compared to the baseline approach with $\varepsilon_{0-130\text{m}}$ sensing inaccuracy. While the offset ranges between 30 m and 95 m for 75 % of the clients using the baseline approach, our combined solution reduces the offset to a range between 15 m and 35 m—an improvement of up to 270 %. At the same time reducing the introduced costs even further. Thus, by incorporating additional available connectivity information as proposed with our combined approach the achieved sensing accuracy can benefit strongly. At the same time decreasing the introduced cost significantly. However, the functionality of the combined approach is strongly dependent on the quality of the delivered monitoring data as the selection of anchors for the location retrieval and the selection of gateways for AdaptMon.KOM is based on this data.

Cost reduction & improved accuracy

Figure 32b and Figure 32c confirm these findings, which show the offset over time and the ratio of cost-intensive measurement states on the clients for different anchor fractions. With $\varepsilon_{0\text{m}}$ and $\varepsilon_{0-15\text{m}}$ the combined approach cannot deliver the same location accuracy as the baseline. However, the introduced costs are reduced by a multitude as visible in Figure 32c. Considering the $\varepsilon_{0-130\text{m}}$ sensing error, the potential of our combined approach becomes apparent as it outperforms the baseline with respect to the achieved sensing accuracy and the introduced costs. The anchor fraction of 40 %, almost matches the achieved offset compared to using an anchor fraction of 75 %. Both configurations double the achieved average sensing accuracy as the average offset is reduced by 50 %. The results show that for cost-critical applications location sensing techniques relying on, e. g., Wi-Fi, it is sensible to select fewer anchors and to rely on the position estimations achieved by our combined usage of AdaptMon.KOM and AssignMe.KOM. Practically, this further decreases the introduced costs for smaller anchor fractions compared to the baseline approach (see Figure 32c).



(a) Fairness (FI(x)) of the load (b) Ratio of cost states (c) Avg. offset over time

Figure 33: Fairness, cost and offset comparison for the combined use of AssignMe.KOM and AdaptMon.KOM with different anchor selection strategies (40 %) compared to the baseline approach with GPS-assisted position sensing and ε_{0m}.

The box ranges of the cost-intensive measurement states indicate an unfair distribution of the localization load among clients (see Figure 32c). For an anchor fraction of 40 %, the active measurement states make up between 18 % and 70 % of all states on the clients (including deactivation and no measurement). Thus, we analyze the impact of different anchor selection strategies on the introduced cost and, very importantly, the achieved fairness of the cost-intensive measurement task. For the anchor selection, we rely on the strategies presented in Figure 5.5. The fairness index FI(x) shown in Figure 33a reveals that the fair-cost selection FairCo provides an equal distribution of the measurement task. The quantitative fairness metric FI(x) does not imply to which extent clients perform the cost-intensive measurement task. Thus, we consider the ratio of cost for the measurement states in Figure 33b. It shows that the baseline approach may show high fairness, however only as all clients measure every time. The FairCo selection achieves perfect fairness $FI(x) = 1$ and at the same time only relies on a subset of anchor clients (40 %) to retrieve the location information for all clients continuously. Compared to the MinCo selection strategy, where anchors are selected once and then used for all subsequent measurement tasks, FairCo guarantees for load fairness in the network as visible in Figure 33a. The large box range for the MinCo selection strategy as visible in Figure 33b is reasoned by the characteristic that MinCo uses a set of clients that is selected once to perform the measurements, while all other clients never measure their position. Achieving a fair resource share also improves the lifetime of the entities in the network in the resource-constrained environment of mobile networks [116, 117].

Improved fairness & client lifetime

With our combined solution, the potential for dynamic reconfiguration over time by using transitions is given. Other than with the de facto standard, our approach allows the adaptation of the localization approach to fluctuating environments conditions and more important to changing requirements. The evaluation results show that, depending on the location sensing technology, the combined usage of AssignMe.KOM and

ADAPTMON.KOM reduces the introduced cost significantly and improves the achieved sensing accuracy and the fairness among users. However, both mechanisms are mutually dependent as with decreasing monitoring accuracy also the data basis for the selection of anchors becomes less precise. Thus, the likelihood for wrong decisions when selecting locations measuring points increases. This combined consideration of (transition-enabled) mechanisms is especially important for network management services such as monitoring, as those deliver the required information for adaptations.

Fair & accurate position retrieval at lower costs

Overall, our evaluation results show the great potential of transitions in the domains of offloading and monitoring. The centralized and decentralized coordination of the transition-enabled offloading service ASSIGNME.KOM enables together with the execution of transitions a significantly improved flexibility. By executing transition between gateway selection strategies during runtime, the service can represent different utility functions, such as fairness and low-cost, and adapt to changing requirements. We showed the usage of extensive transition coordination to allow for a wide utility range from robust and reliable coordination to low overhead coordination by piggybacking transition information on sent messages. In environments with coexistent transition-enabled mechanisms the more complex reconfigurations are necessary. We showed that with our introduced methodology for inter-proxy state transfer, loss of relevant data in transition plans covering a multitude of transition-enabled mechanisms can be reduced or even prevented.

7

SUMMARY, CONCLUSIONS, AND OUTLOOK

Transitions are an essential step towards seamless monitoring and offloading of dynamic mobile networks. In this chapter, we summarize the contents of this thesis. We state our main contributions in the domains of transitions, monitoring, and network offloading. Based on the results obtained in this work we draw conclusions. Finally, we point out open issues and potential future work.

7.1 SUMMARY OF THE THESIS

In Chapter 1, we described the challenges in communication networks that result from connectivity and traffic demands of users. We motivated the utilization of monitoring and offloading paradigms to capture and handle the needed information in the networks, as detailed in Chapter 2. To handle the dynamics of mobile networks, the heterogeneity of network entities, and to enable the best possible utilization of specialized solutions we propose concepts for transitions within monitoring and network offloading. We surveyed and discussed recent solutions for mobile network monitoring and offloading through gateway selection and clustering in Chapter 3. Additionally, we studied use cases of transitions in other research domains. Based on our analysis of the state-of-the-art we presented the following contributions in our thesis.

7.1.1 *Contributions*

Transition Coordination & Spreading

Inter-proxy state transfer

We enabled transitions within network offloading and monitoring to handle the dynamics of surrounding environments. For the execution and spreading of transitions we advanced the field of transition coordination and state transfer within complex transition plans. We proposed transition coordination approaches for a wide utility range from robust and reliable coordination to low overhead coordination by piggybacking transition information on sent messages. We significantly advanced the field of state transfer during transitions for coexisting mechanisms in which more complex reconfigurations are necessary. By introducing a methodology for inter-proxy state transfer, we prevented the loss of relevant data in transition plans covering a multitude of transition-enabled mechanisms. We showed the great potential of combining network offloading and monitoring on the example of our contributions in the area of location-based services. Finally, we contributed models to the Simonstrator.KOM platform for mobility and social interaction between clients and heterogeneous connectivity scenarios as detailed in Chapter 6. We integrated design abstractions of our contributions and transition methodologies to the Simonstrator.KOM, which we used as the foundation for our extensive evaluation.

AssignMe.KOM, as presented in Chapter 4, is a service to support the integration of a multitude of gateway selection and clustering solutions for offloading. It constitutes our *first contribution* allowing for transitions to handle the dynamics of network conditions and application requirements. We propose and realize a concept for transitions between gateway selection and clustering approaches in this service. Furthermore, we introduce organizational structures within the service to allow for transition between centralized and decentralized patterns. We identified six main classes of gateway selection approaches and encapsulated their main functionalities into AssignMe.KOM, allowing us to incorporate recent related work into the service. In doing so, we can represent different utility functions, such as fairness and low-cost, and adapt to changing requirements during runtime by executing transitions between the gateway selection approaches. To consider changing relations between the clients, AssignMe.KOM allows for transitions between specialized clustering solutions. We target the centralized and decentralized coordination of the service by introducing client- and server-side components that also share the assignment results within the service. In order to enable transitions between decentralized approaches, we introduced and realized a phase-based concept for the decentralized selection and clustering solutions to live up to the challenges of the ad hoc environment. Compared to existing work on gateway selection and clustering in mobile networks our solution allows for transitions between specialized solutions, thus significantly improving the flexibility of offloading. Additionally, our solution enables unprecedented comparability of these specialized solutions. Furthermore, we showed the potential of the generic service in a multitude of application domains [123–125, 149, 153, 161].

Transitions between gateway selection approaches

Centralized & decentralized organization

Inter-domain applicability

With our *second contribution*, we target the development and realization of a transition-enabled monitoring service as presented with AdaptMon.KOM in Chapter 5. To allow for transitions between monitoring mechanisms we proposed a methodology for the separation of the monitored systems from the monitoring service. Furthermore, we introduced a methodology for the encapsulation of local collection and dissemination mechanisms to allow AdaptMon.KOM to represent different mechanisms. We extended and deployed this methodology to upload and download mechanisms used in centralized and hybrid monitoring.

Separation & encapsulation

. . . to allow for transitions.

7.1.2 *Conclusions*

In our in-depth simulation-based evaluation, we assessed the characteristics and effects of transition execution and coordination in mobile networks on monitoring and offloading systems. Our evaluation results show that the efficient and cost-effective monitoring of dynamic and heterogeneous environments is possible by realizing transitions in the monitoring service. We compared the characteristics of non-adaptive systems and transition-enabled mechanisms in our evaluation and showed that transitions contribute significantly to the reliability of a mechanism. To assess the impact of transitions in different dynamic scenarios, we modeled an overload and a recovery scenario of a communication network to cover important effects observed in today's networks. Both transition-enabled services can execute transition plans seamlessly during runtime. We validated the benefit of inter-proxy state transfer for complex transition plans that cover multiple coexisting transition-enabled mechanisms and showed the significant impact of this data recovery methodology during transitions in comparison to transition-enabled mechanisms without inter-proxy state transfer. Our results reveal that transitions between gateway selection strategies have a stronger impact on the utility of an offloading mechanism and its dependent systems than transitions between clustering strategies. We demonstrated the coexistence of transition-enabled mechanisms, whose functionalities fuse to a transition-enabled service. We analyzed the coexisting behavior of transition-enabled mechanisms for the individual contributions. In our evaluation, we reveal that the coordination and the spreading of transition decisions in the network have a strong influence on the success of the adaptation due to challenges such as incompatibility and mobility of clients. Especially the coordination strategy used for transitions in mobile networks has a major impact on the cost, the latency of transition executions in the network, and the reliability of the transition execution. The combined utilization of our contributions showed that relevant utility functions such as fair distribution of resources or minimal overhead can be achieved and adapted during runtime on changing requirements. On the exemplary use-case of location-based services, we manifested a cost-efficient and reliable methodology for location retrieval. By allowing for transitions in monitoring and offloading of mobile networks, we adapt to dynamic environmental conditions and changing requirements—a possibility not offered by the de facto standard.

7.2 OUTLOOK

Our evaluation results motivate the investigation of the concept of transitions within monitoring and offloading in other network research areas. The communication demand and network status information are essential in the aftermath of a disaster [130]. Both of our contributions can provide for decentralized monitoring and role assignment to organize entities in an infrastructure-less post-disaster environment. However, while current mechanisms for decentralized monitoring mostly rely on individual decisions for communication, the need for resource-saving monitoring mechanisms that allow for collaboration among the clients is great.

Disaster response scenarios

Vast amounts of data are available in highly heterogeneous smart urban environments, with vehicles, IoT sensing entities, and humans where networks of different dimensions are formed relying on communication means such as Wi-Fi, ZigBee, and cellular infrastructure support. In such dynamic environments the assessment of the quality and relevance of information and their sources constitute an open challenge.

Information relevance & quality

We considered the process of adaptation by reactively executing transitions, as detailed in Chapter 1. To improve the impact of transitions in highly dynamic environments the execution of transitions based on the prediction of the network state is preferable. The proactive execution of the former is relevant to minimize or even prevent service degradations due to a reactive execution of transitions. During the process of data collection and dissemination within monitoring and offloading, security and privacy of the shared information and the user are an asset that is to be

Proactive execution

protected. Integrating security and privacy-protecting mechanisms into the collaborative nature of our contributions can help in preventing malicious users from hijacking the mechanisms.

Our contributions for monitoring and network offloading have clearly shown the need and the potential of transitions in both domains, while the realization and generalization of our contributions within the Simonstrator.KOM have successfully paved the path for further research in the respective fields.

ACKNOWLEDGMENTS

This work has been funded by the German Research Foundation (DFG) as part of project B1 within the Collaborative Research Centre (CRC) 1053 "MAKI – Multi-Mechanisms Adaptation for the Future Internet".

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A

APPENDIX

A.1 DETAILED VIEW ON ADAPTMON.KOM

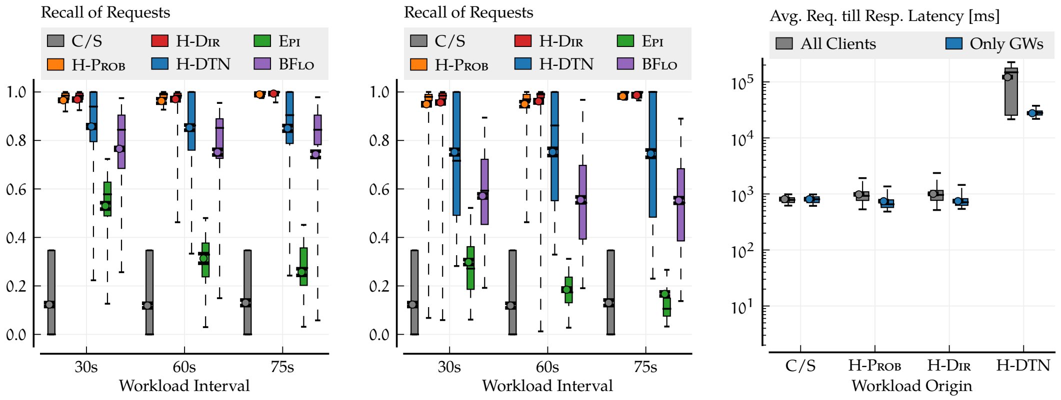
This section provides further details on the characteristics of AdaptMon.KOM, introduced in Chapter 5. The following evaluation results are obtained in the same setups as presented in Section 6.2 if not otherwise stated.

Impact of the Workload Interval and the Workload Origin

It is important that a monitoring service is robust against different load situations. We utilize the constant scenario configuration DA with a cellular connectivity of 35 %. The structure used in AdaptMon.KOM and the resulting monitoring mechanisms are robust against workload interval changes as visible in Figure 34.

This is due to the merging of monitoring data in the local and cellular communication processes used in AdaptMon.KOM. We can observe that the monitoring mechanisms deliver comparable recall for the requests and responses for a constant scenario (DA) with different workloads (see Figure 34a). Only the decentralized monitoring mechanism Epi is affected by less a high workload interval. The reason for that is, that Epi is dependent on a certain communication frequency and load in the network to perform reliably. Thus, with less requests in the network, less ad hoc communication takes place. The same is observable for the recall of requests in the NY mobility model in Figure 34b.

However, the effect of less communication within in the decentralized monitoring mechanisms Epi has a stronger impact in the grid-based structure of the map in NY. The centralized monitoring mechanism C/S delivers only the monitoring data from gateways. In this setting with a maximum of 35 % cellular connectivity $C_{\uparrow\downarrow}$ it is likely that requests are invoked on non-gateway clients and are lost. The workload origin W_O impacts the latency from request invocation till response reception significantly as visible in Figure 34c. A reason for this is that requests invoked on gateways are distributed faster in the centralized and hybrid monitoring mechanisms. Additionally, to the shorter distributions path, a reduced path from the responder to the requester as a last response dissemination step can be saved in most cases. With all clients being selected as the target of the requests in the evaluation in Section 6.2 the achieved precision of the monitoring approaches is perfect. Within current mobile monitoring approaches (see Chapter 3) the targeted addressing of individual clients is mostly neglected. Controlling the distribution of requests to a subset of clients as it is done for example in publish/subscribe systems [148], would add additional overhead to the monitoring process. Thus, when we consider a limited set of targeted clients for requests the monitoring systems used will not use special procedures to only address



(a) Request recall (DA)

(b) Request recall (NY)

(c) Latency from request till response (DA)

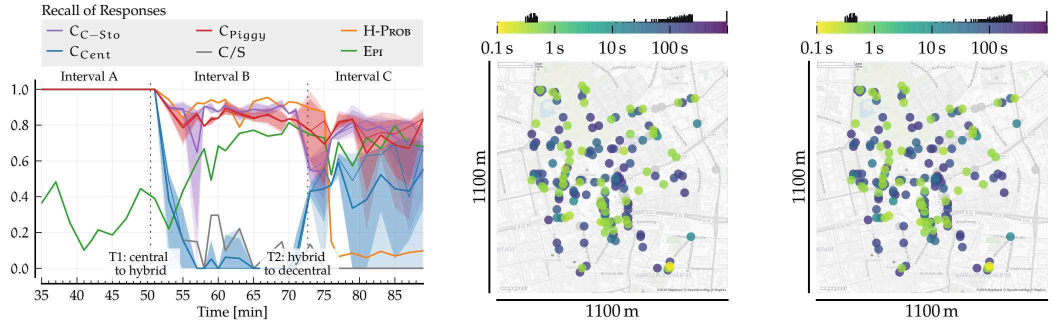
Figure 34: Workload interval changes in the DA and NY scenarios with 35 % cellular connectivity $C_{\uparrow\downarrow}$. Workload origin W_O impact on the latency from request invocation till response reception.

the targeted clients of the requests. Thus, the precision within AdaptMon.KOM is currently a function of the achieved recall of the distribution of requests and responses and the ratio of targeted clients in the network.

Transitions in Fluctuating Environments

In the following we assess further results of the impact of transitions within AdaptMon.KOM in the in Section 6.2.1 introduced scenarios. The simulation setup remains the same as in Section 6.2.2.

Based on our observation of the recall of requests in the overload scenario in Figure 27a, we can see that the achieved recall of monitoring responses depends on the environment as visible in Figure 35a. Comparing the transition spreading results obtained with the two different coordinators $C_{\text{C-Sto}}$ in Figure 35b and C_{Piggy} Figure 35c, we can see that $C_{\text{C-Sto}}$ reliably distributes the transition decision in the network. All online clients receive the transition within the round-trip-time of the cellular network. Clients that join the network later, as a characteristic of the overload scenario, receive the transition decision afterwards. The clients executing the transition later than 1000 s are reasoned in the second churn period 20 min after the first churn. The execution with C_{Piggy}, shown in Figure 35c, clearly indicates the dependency of the approach to the location of clients invoking the transition. Adjacent clients execute the transition with the next message received from the time-limited periodic broadcast in C_{Piggy} as explained in Section 6.2.2. Clients far away from the originating client receive the transition decision not until monitoring data arrives at the clients. This behavior is visible in the ratio of mechanism utilization in Figure 36a for $C_{\text{C-Sto}}$ and Figure 36b for C_{Piggy}. We can see that with C_{Piggy} some clients do not receive the transition decision

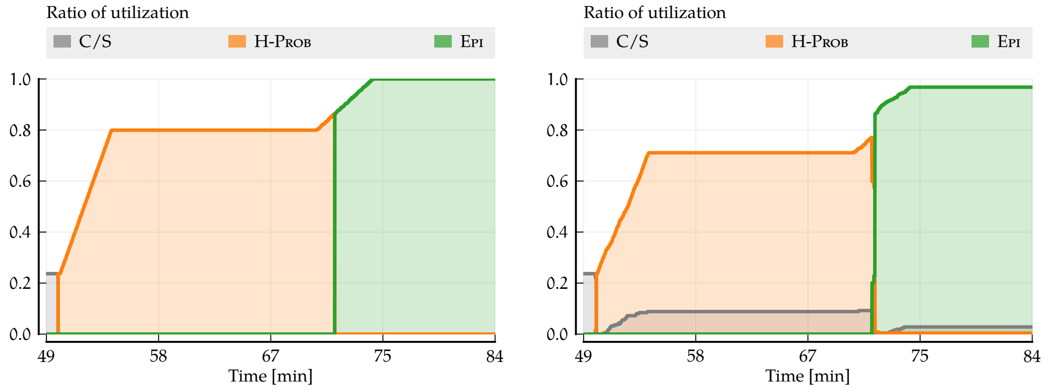


(a) Recall of responses (b) Spread T1 ($C_{\text{C-Sto}}$) (c) Spread T1 (C_{Piggy})

Figure 35: Recall of responses and transition spreads for T1 with $C_{\text{C-Sto}}$ and C_{Piggy} in the DA overload scenario.

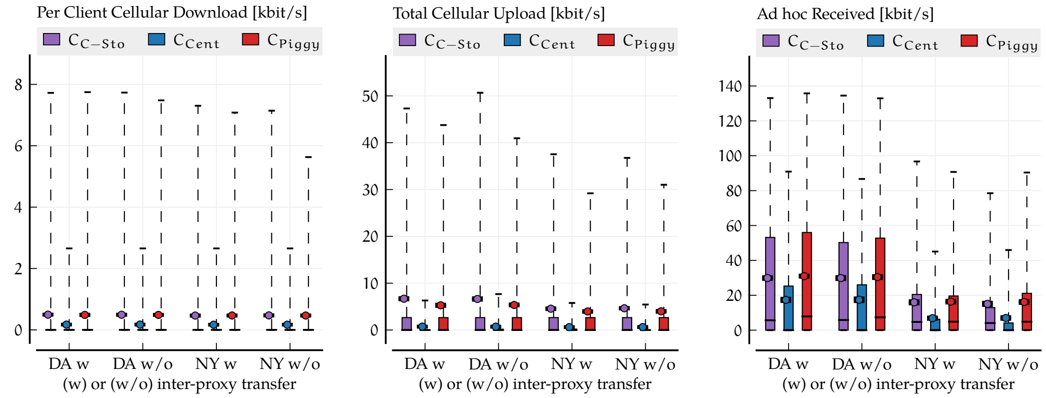
for a longer period compared to $C_{\text{C-Sto}}$. However, at the cost of additional traffic for the coordination of the transition Figure 30c.

Considering the traffic of the monitoring in the cellular network in Figure 37, we can see that AdaptMon.KOM is introducing very little additional load per client. At most $8\,^{\text{kbit}}/_{\text{s}}$ are downloaded per client as shown in Figure 37a. For the total cellular upload shown in Figure 37b we see the similar picture. At most $50\,^{\text{kbit}}/_{\text{s}}$ of additional cellular traffic for the whole monitoring process in AdaptMon.KOM. The significant positive effect of inter-proxy state transfer on the performance of the monitoring service, detailed in Section 6.2.3, has no strong impact on the cellular or ad hoc communication in the network as visible in Figure 37c. Comparing the received ad hoc traffic in the overload scenario for both DA and NY, shown in Figure 37c, we can see significant differences of the occurring ad hoc traffic. Clients are likely to take different routes between two end points in the grid-based map structure of NY, which



(a) Mechanims utilization ($C_{\text{C-Sto}}$) (b) Mechanims utilization (C_{Piggy})

Figure 36: Mechanism utilization in the DA overload scenario with $C_{\text{C-Sto}}$ and C_{Piggy}.



(a) Per client cellular download (b) Total cellular upload (c) Ad hoc received

Figure 37: Cellular up- and download per client and local ad hoc received traffic in the overload scenario.

is leading to less communication on same paths which is reducing the performance of the monitoring as not that many messages are received in the local ad hoc network.

Considering the number of transition initiators we compare the spreading of transitions with one or five clients as initiators in the NY overload scenario in Figure 38. For the comparison we rely on the coordinators $C_{\text{C-Sto}}$ and C_{Piggy}. The spreading efficiency with $C_{\text{C-Sto}}$ is not strongly affected by five initiators as also with one initiator the transition decision is uploaded to the central entity and distributed to all affected clients from there using the cellular network as visible in Figure 38a. Thus, most of the clients in the network receive the transition within the round-trip time of the cellular network. For the C_{Piggy} coordination of transition the number of transition initiators has a more significant role as visible in Figure 38b and Figure 38c. We can see that more clients receive the transition within 100 ms and that most of the clients receive the transition within 200 s from the first execution in the network. For the C_{Piggy} the spreading of the initiators over the map has a great impact on the success of the coordination approach.

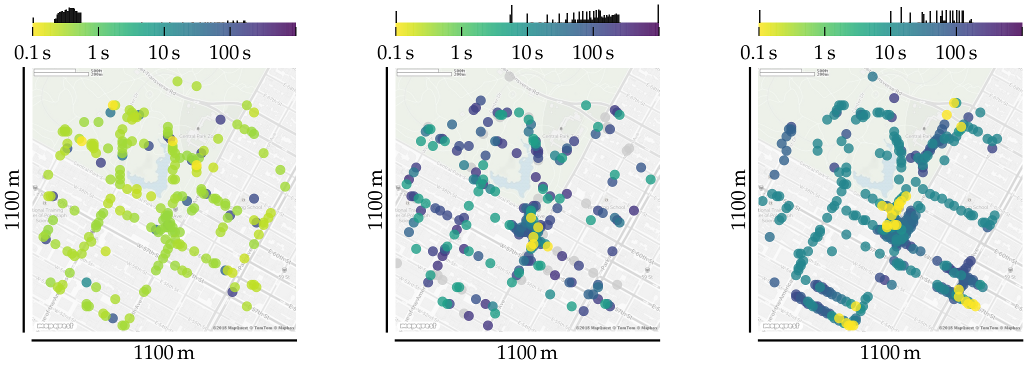
A.2 TRANSITIONS IN OFFLOADING TO REFLECT CHANGING NEEDS

The combination of cellular infrastructure-based communication and wireless (on-demand) communication, such as in MANETs or Wi-Fi assisted networks, is a key characteristic of offloading as introduced in Section 2.4. Offloading allows for more flexibility within mechanisms and applications. With AssignMe.KOM we propose the usage of transitions between specialized selection and clustering approaches. This allows the handling and adaptation to changing network conditions and application requirements within AssignMe.KOM.

We focus on the transitions between different configurations of AdaptMon.KOM in the following. We rely on the constant scenario with the either the DA or NY map-based environments as used in Section 6.2. A more detailed study of the characteristics of the framework on different environmental conditions, application requirements, and fairness metrics can be found in [153, 157, 158, 161]. Application-related evaluations of the offloading framework AdaptMon.KOM from domains other than network monitoring can be found in [124, 148, 149] as detailed in Section 4.4.

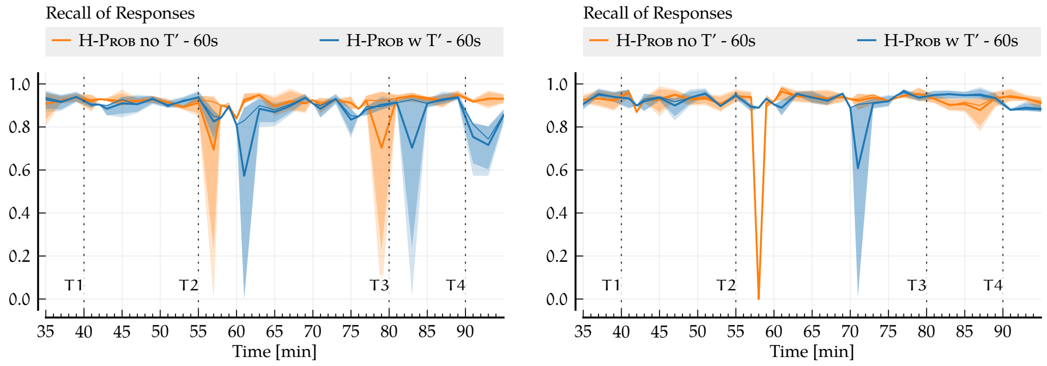
We execute four transitions $[T1 - T4]$ in the network with central transition coordination (C_{Cent}). Those are T1 from LEACH [77] to ALEACH [1], both centralized, *i)* T2 from ALEACH to decentralized DEEC [140], *ii)* from DEEC to centralized ALEACH again and *iii)* with T4 back to a decentralized configuration with decentralized LEACH.

In Figure 39 we can observe that in the time intervals with the decentralized configuration of AssignMe.KOM H-Prob is delivering slightly more fluctuating results for the recall of the responses in the NY scenario (see Figure 39a) compared to the DA scenario (see Figure 39b). This is reasoned in *i)* the less efficient spreading of the monitoring data of H-Prob in the grid-based environment of NY and *ii)* a similar less efficient spreading of information between the clients in the decentralized configuration. With less information on the neighboring clients AssignMe.KOM cannot deliver the same results in the decentralized configuration as in the centralized.



(a) Five initiators ($C_{C\text{-}Sto}$) (b) One initiator (C_{Piggy}) (c) Five initiators (C_{Piggy})

Figure 38: Transition spread with one initiator and five initiators using the C_{Piggy} and $C_{C\text{-}Sto}$ in the NY overload scenario.

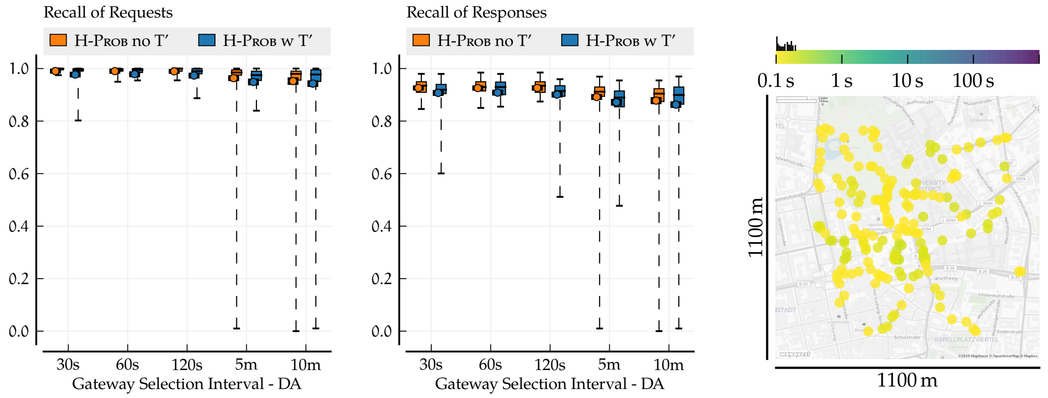


(a) NY

(b) DA

Figure 39: Recall of responses of H-Prob using AssignMe.KOM with a selection interval of 60 s with and without transitions (C_{Cent}). In the DA and NY scenario with a constant density of 165 clients/km^2.

We can see that both the recall of requests and responses are not impacted significantly by the system performing transitions or not, according to Figure 40a and Figure 40b. However, the difference is only showed for the AdaptMon.KOM in the H-Prob configuration, thus for other applications the resulting impact of an inaccurate selection of gateway and clusters due to transitions to, e. g., decentralized strategies must be assessed. The gateway selection interval on the other hand has an effect on the performance of the monitoring mechanism H-Prob. With frequent updates if the gateway selection and establishment of clusters in the mobile network the distribution of the relevant gateway within AdaptMon.KOM is guaranteed. Furthermore, does a higher selection interval improves the responsiveness of a system to changes. The impact of the selection interval of AssignMe.KOM is application-specific. We triggered the transition within AssignMe.KOM on the server-sided component with central coordination C_{Cent}, see Section 4.4 for details. Thus, the transition spreading of T3, as visible in Figure 40c, reveals the one-hop cellular delivery of the transition decision.



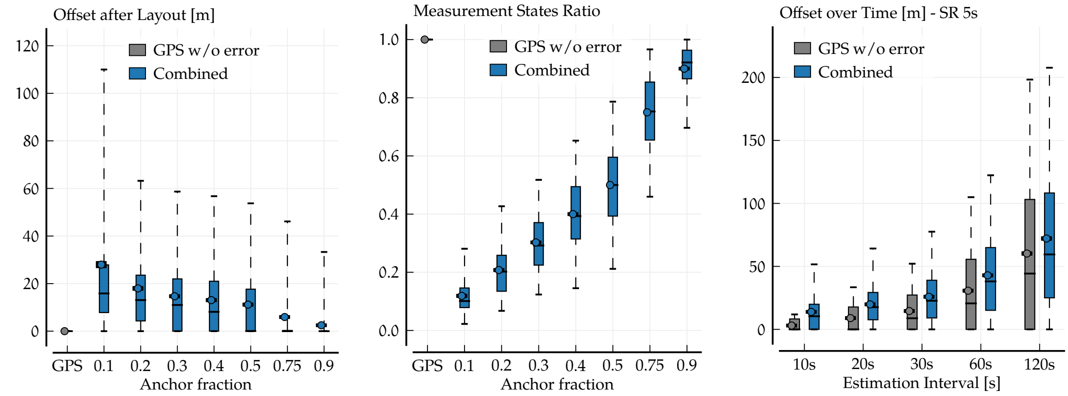
(a) Recall of requests (b) Recall of responses (c) Transition spread T3

Figure 40: Comparison of the recall of requests and responses of H-Prob for different selection intervals of AssignMe.KOM with and without transitions. Transition spread for T3 using the C_{Cent}. All in the DA scenario with a constant density of 165 $\text{clients}/\text{km}^2$.

A.3 DETAILED VIEW ON COLLABORATIVE MONITORING

In the following we discuss additional results for the combined location retrieval approach introduced in Section 5.5. The results shown here are based on our previous work [153]. Similar as the gateway ratio in AssignMe.KOM, we can see that the ratio of anchors within the combined approach influences the estimation accuracy of the location retrieval. With fewer anchors selected more positions must be estimated using the graph relations between the clients. We compare the Select-and-Layout (SL) composition strategy using the Negative Interference (NegInt) selection for anchor fractions between 10 % and 90 % in Figure 41. The baseline approach uses 100 % of the clients in the network as anchors. The achieved position estimation accuracy with only 40 % of the clients as anchors is less accurate than the baseline approach with zero-error localization as shown in Figure 41a. Nevertheless, with location estimation errors ranging between 0 m and 20 m for three quarters of the clients (box range) the achieved accuracy is sufficient for many applications. Still, a location estimation error of up to 55 m is possible for not well-connected clients with few neighbors. This happens mostly when chains of clients with only two adjacent clients each establish in the underlying connectivity graph.

When more clients are selected as anchors, the offset improves as more location fixing points can be used in the layout of the SL composition scheme. Looking at the location error introduced by the combined location estimation, one has to take the reduces cost into account. As shown in Figure 41b, our proposed location estimation approach is significantly reducing the introduced costs as the ratio of cost-intensive measurement state is reduced drastically. Our approach reduces the ratio of clients performing active measurement by a factor larger than two in average when using 40 % of the clients as anchors. Obviously, the cost as a function of the introduced measurement states show a linear dependency to the anchor fraction in our approach.



(a) Offset after the layout (Anchor fraction) (b) Ratio of cost states (Anchor fraction) (c) Offset over time (Estimation interval)

Figure 41: Impact of the anchor fraction and the round length on the combined approach for location retrieval.

The box ranges, however, indicate an unfair distribution of the measurement task among the clients, which is reasoned in the used NegInt anchor selection strategy. Active measurement states on clients, as visible in Figure 41b, make up between 18 % and 70 % of all states on the clients (including *deactivation* and *no measurement*). We observed the same when comparing different anchor selection strategies in Figure 33a in Section 6.3. Surprisingly, the used clustering approach does not have a strong influence on the estimation quality or introduced costs. While the anchor selection strategy has a direct effect on the clients that perform the measurement, clustering *only* groups the clients in the network, which only has a indirect impact on the followed selection. The round length of the selection of clients, thus the estimation interval in the network has a strong impact on the achieved offset of time as visible in Figure 41c. We compare location estimation intervals between 10 s and 120 s. We can see that with longer estimation intervals, the position estimation quality of the baseline approach degrades significantly. With estimation intervals of 30 s or longer the achieved position offset of our combined approach approaches the results of the baseline. And this at a fraction of the costs.

A.4 LIST OF ACRONYMS

APs	Access Points
AutReg	Autoregressive Filter
C/S	Client/Server
CBC	Connection Based Clustering
CSL	Cluster-Select-Layout
DBScan	Density-Based Spatial Clustering Of Applications With Noise
DTNs	Delay-tolerant Networks
ExpSmo	Exponential Smoothing
GPS	Global Positioning System
IoT	Internet Of Things
k-Means++	K-Means++ Clustering
MANETs	Mobile Ad Hoc Networks
MAPs	Monitoring Access Points
MIB	Management Information Base
NL	No Learning
OSM	OpenStreetMap
QoE	Quality Of Experience
QoS	Quality Of Service
SDN	Software-defined Network
SDWN	Software-defined Wireless Network
SIS	State Information System
SL	Select-and-Layout
SLC	Select-Layout-Cluster
SNMP	Simple Network Management Protocol
TCP	Transmission Control Protocol
TTL	Time To Live
UDP	User Datagram Protocol
Wi-Fi	Wireless Fidelity

A.5 SUPERVISED STUDENT THESES

[1] Simon Braunstein. “Graph-based Topology-analysis of an adaptive Monitoring System.” Master Thesis. TU Darmstadt, 2016.

[2] Tim Feuerbach. “Allocation Strategies for physical Energy-Resources in Ad-hoc Networks.” Master Thesis **(Best Thesis of the Year 2017)**. TU Darmstadt, 2017.

[3] Jonas Hülsmann. “Latency Optimization in mobile Networks.” Bachelor Thesis. TU Darmstadt, 2016.

[4] Clemens Krug. “Ressource Allocation in Automotive Scenarios.” Bachelor Thesis **(Best Thesis of the Year 2018)**. TU Darmstadt, 2017.

[5] Karsten Kruse. “Reconfigurable Monitoring in Dynamic Networks for Gateway-Selection Algorithms.” Master Thesis. TU Darmstadt, 2016.

[6] Simon Luser. “Adaptive Prioritization Mechanisms for Post Disaster Communications.” Master Thesis. TU Darmstadt, 2017.

[7] Marc Schiller. “Transitions between Monitoring Schemes in Mobile Networks.” Master Thesis. TU Darmstadt, 2017.

[8] Max Stiegler. “Data Dissemination as a Service for Edge-Networks.” Bachelor Thesis. TU Darmstadt, 2017.

[9] Christoph Storm. “Collaborative Location Retrieval under Data Uncertainty.” Master Thesis. TU Darmstadt, 2017.

[10] Michael Walter. “Gateway Selection in Mobile Multi-hop Networks.” Master Thesis. TU Darmstadt, 2016.

B

AUTHOR'S PUBLICATIONS

MAIN PUBLICATIONS

[1] Nils Richerzhagen, Roland Kluge, Björn Richerzhagen, Patrick Lieser, Boris Koldehofe, Ioannis Stavrakakis, and Ralf Steinmetz. "Better Together: Collaborative Monitoring for Location-based Services." In: *Proceedings of the 19th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. IEEE, 2018, pp. 1–9.

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[5] Nils Richerzhagen, Björn Richerzhagen, Rhaban Hark, Dominik Stingl, and Ralf Steinmetz. "Limiting the Footprint of Monitoring in Dynamic Scenarios through Multi-dimensional Offloading." In: *Proceedings of the International Conferece on Computer Communication and Networks (ICCCN)*. IEEE, 2016, pp. 1–9.

[6] Nils Richerzhagen, Björn Richerzhagen, Boris Koldehofe, and Ralf Steinmetz. "Towards Transitions between Role Assignment Schemes: Enabling Adaptive Offloading in Challenged Networks." In: *Proceedings of the 12th Workshop on Challenged Networks (CHANTS) co-located with 23rd Annual International Conference on Mobile Computing and Networking (MobiCom)*. ACM, 2017, pp. 1–6.

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CO-AUTHORED PUBLICATIONS

[10] Daniel Burgstahler, Ulrich Lampe, Nils Richerzhagen, and Ralf Steinmetz. "Push vs. Pull: An Energy Perspective." In: *Proceedings of the 2013 6th IEEE International Conference on Service Oriented Computing & Applications (SOCA)*. IEEE, 2013, pp. 190–193.

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C

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EDUCATION

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10/2009-04/2013	Technische Universität Darmstadt, Bachelor studies in Electrical Engineering and Information Technology Degree: Bachelor of Science
08/2006-06/2009	Berufskolleg am Haspel, Wuppertal, Nordrhein-Westfalen, Germany, Degree: Allgemeine Hochschulreife

ACADEMIC EXPERIENCE

Since 02/2015	Researcher funded by DFG (German Research Foundation) in the Collaborative Research Centre (CRC) 1053 – MAKI "Multi-Mechanismen-Adaption für das künftige Internet"

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Since 02/2015	Technische Universität Darmstadt, Research assistant at the research group Adaptive Overlay Communications at the Multimedia Communications Lab (KOM)

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Since 2015	Seminar “Advanced Topics in Future Internet Research”, Organizer and Supervisor.
Since 2016	Lecture “Communication Networks II”, Teaching Assistant.

Darmstadt, January 21st, 2019

Nils Richerzhagen

D

ERKLÄRUNG LAUT PROMOTIONSORDNUNG

§8 Abs. 1 lit. c PromO

Ich versichere hiermit, dass die elektronische Version meiner Dissertation mit der schriftlichen Version übereinstimmt.

§8 Abs. 1 lit. d PromO

Ich versichere hiermit, dass zu einem vorherigen Zeitpunkt noch keine Promotion versucht wurde. In diesem Fall sind nähere Angaben über Zeitpunkt, Hochschule, Dissertationsthema und Ergebnis dieses Versuchs mitzuteilen.

§9 Abs. 1 PromO

Ich versichere hiermit, dass die vorliegende Dissertation selbstständig und nur unter Verwendung der angegebenen Quellen verfasst wurde.

§9 Abs. 2 PromO

Die Arbeit hat bisher noch nicht zu Prüfungszwecken gedient.

Darmstadt, 21. Januar 2019

Nils Richerzhagen