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Inter-Generational Transitions in Technological Ecosystems: The Case of Mobile Telephony

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INTER-GENERATIONAL TRANSITIONS IN TECHNOLOGICAL ECOSYSTEMS: THE CASE OF MOBILE TELEPHONY[1]

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Abstract

Many technology studies have conceptualized transitions between technological generations as a series of S-curve performance improvements over time. Surprisingly, the interregnum between successive technological generations has received little attention. To understand what happens in the interregnum, we build upon a framework of technological change as happening within an ecosystem that is characterized by both momentum and inertia. Applying this framework to study the mobile communications ecosystem, we found that the transition between 2G to 3G wireless was far from sequential. Different parts of the ecosystem evolved at different rates exerting both inertia and momentum with "collateral technologies" playing an important role in shaping the transition path that unfolded. Based on this study we suggest that, rather than a distinct or unitary shift from an old to a new technology, transitions proceed in a zigzag manner resulting in the emergence of hybrid technologies. These processes hold implications for both theory and practice that we explore in this paper.

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Many studies on technological cycles, discontinuities, paradigms and trajectories are predicated on Schumpeter's (1934, 1942) analysis of creative destruction whereby waves of discontinuous technological change destroy old industries to create new ones (cf. Christensen, 1997; Foster 1986; Hill & Rothaermel, 2003; Tushman & Anderson, 1986; Utterback, 1994). Technological evolution is usually seen as proceeding in a sequential and progressive manner along an S-shaped curve.[2] The S-curve hypothesis suggests that the performance of a technology, slow at first, increases at a faster rate, finally flattening out to be supplanted by a new technology with its own S-curve.

The S-curve of technological evolution or the diffusion path of novel technologies (e.g., Griliches, 1957) has been highly influential, especially in suggesting the point at which managers should shift investments from a mature technology to a new one. The S-curve has been used to depict the diffusion pattern of not just novel technologies and products, such as laser printing (Christensen 1997), process technologies (Karshenas & Stoneman, 1993) and mini-mills (Tushman & Anderson, 1986) but also a wide range of innovative social practices (e.g. Rogers, 2003; Strang & Soule, 1998).

Yet, those who have examined micro-processes involved in such transitions suggest that there is more than a simple linear shift from one technological system to another (Sood & Tellis, 2004; 2005). Old technologies can prove surprisingly resilient and don't simply get eclipsed by new ones (Henderson, 1995). Instead, they may evolve through an "irregular step function" with big random improvements in performance, following long periods of dormancy (Sood & Tellis, 2004). Also, major advances within a technology regime can also drive the evolution of

[2] The S curve is has also been used in the innovation literature (Rogers 2003; Utterback 1994) to explain the diffusion rate of most innovations. Only a small number of people adopt an innovation at first, and then the adoption rate increases sharply, followed by a slowing of the laggards adopting the innovation.

technologies (Lawless & Anderson, 1996). Moreover, different interrelated constituents of the socio-technical ecosystem evolve at different rates (Adner, 2006; Hughes, 1987, MacKenzie, 1987) mediated by bottlenecks (Rosenberg, 1982) and "reverse salients" (Hughes, 1983: 73). In sum, the transition from an old technology to a new one is neither inevitable nor sequential.

What are the processes that may characterize inter-generational transitions? We address this question by analyzing the mobile communications industry that has often been marked by technological shifts. In particular, we study the dynamics in the *interim* period between the second and third generation technologies. To do so, we adopt a perspective that allows us to examine the diverse pulls and pushes created by constituents. Our study suggests that, rather than the "winner takes all" tipping effects, or the inertia caused by "lockouts" and high switching costs (David, 1985; Schilling, 2003), technological transitions may be characterized by both momentum and inertia. As a result, technological transitions are not necessarily *unitary* shifts from the old to the new, but, instead may be characterized by uneven movements that generate asynchronies or imbalances across the ecosystem during the migration process. By highlighting these processes, we offer a more multifaceted conceptualization of technological transitions that includes the institutional and ecological dynamics and carries important caveats for premature jumps to the next technological phase.

THEORETICAL FRAMEWORK

Schumpeter's (1934, 1942) seminal work on creative destruction has inspired a rich body of literature on technological cycles, discontinuities, paradigms and trajectories (Dosi, 1982; Tushman & Anderson, 1986; Utterback, 1994). An increasingly popular hypothesis on technological evolution as captured by the image of an S-curve continues to attract much scholarly attention (Christensen, 2006; Danneels, 2006; Tellis, 2006). While an S-curve is useful in depicting the outcomes of a battle between technological generations once it has been fought and after a new technology has successfully eclipsed the old, it is less useful to understand the intermediating processes *between* technological generations (Tellis, 2006; Lawless and Andersen, 1996).

Consequently, such studies miss out on a holistic and systematic analysis of the various complementary and supportive elements that constitute a technology ecosystem (Adner, 2006). Iansiti and Levien (2004) note, a biological ecosystem provides a powerful analogy for understanding a business network. Like business networks, biological ecosystems are characterized by a large number of loosely interconnected participants who depend on each other for their mutual effectiveness and survival and who, like business network participants, share their fate with each other. Such an ecosystem may consist of producers from the supply side, users from the demand side as well as institutional players (Adner & Zemsky, 2006; Garud & Karnoe, 2003).

Prior research suggests that the ecosystem may experience several forces that mediate the transition from one technological generation to another. One such force is inertia (Farrell and Saloner; 1986). Inertia is defined as "a socially excessive reluctance to switch to a superior new standard when important network externalities are present in the current one" (Farrell & Saloner, 1986: 940). A new superior standard may not be able to replace a technological standard in place because of installed base effects, lock-ins (Arthur, 1989: David, 1985) and the presence of complementary or co-specialized assets (Teece, 1986). Early adopters whether firms or users, may have to bear a disproportionate amount of the costs of incompatibility, which they may be unwilling to. This can create inertia due to a "penguin effect[3]" (Farrell & Saloner, 1986: 943)

[3] Penguins who must enter the water to find food often delay doing so because they fear the presence of predators. Each would prefer some other penguin to test the water first.

and can impede a collective switch from an existing to the new standard, even if superior (David, 1985). From a demand side perspective, inertia may manifest in customers deciding to postpone the purchase of specific products. Such an "anticipatory retardation" can dampen or even prevent the rapid diffusion of the new technology (Rosenberg, 1982).

Momentum is another force – eagerness to prematurely adopt a standard, because of its perceived advantages over the current technological standard (Farrell & Saloner, 1986: 942). However, it is not just firms that generate momentum for a particular technological standard they are sponsoring. Momentum for a particular technologies or products can also be generated by the collective beliefs engineered by media, environmental groups, analysts and even users (Hughes, 1983; Pollock & Rindova, 2003). For instance, the media and environmental groups have played a significant role in whether nuclear technology is used as a source of energy.

Similarly, momentum may also be generated when users view certain technologies as being legitimate and fashionable (Abrahamson & Fairchild, 1999). For instance, Apple's iPod rapidly became the most successful portable music player based on the MP3 technology, despite competition from viable substitutes. Network externalities benefits (Economides, 1996; Katz & Shapiro, 1985) generated by Apple's fashionable technology and the complementary online music store, iTunes has resulted in Apple selling over 30 million i-pods and over a billion songs in rapid time (The Economist, 2004a).

How do these contradictory forces of momentum and inertia play out during technological transitions? Do constituents of an ecosystem operate in sync or are there temporal discords that emerge during various points of a technological transition? And, how do these processes influence migration paths? We address these questions by providing an in-depth account of the processes involved in the transition between the second and third generation mobile telecommunication technology. But, first, we offer a brief overview of our research site and the methods that we employed in conducting this study.

RESEARCH SITE AND METHODS

We chose to analyze the mobile communications ecosystem between 1999 and 2005 for several reasons. First, we wanted to examine the dynamics of inter generational changes in the wake of a technological discontinuity. The advanced third generation (3G) in mobiles represented such a discontinuity in the mobile ecosystem. Second, the ecosystem had systemic characteristics (Katz & Shapiro, 1985) with interdependent constituents such as network operators, equipment manufacturers and regulators, each with different interests and motivations, vis-à-vis the transition. The system also required inter-operability between the mobile networks, widespread availability of compatible handsets and a reasonably large user-base. Third, the history and events related to transitions within this ecosystem are well documented providing a rich context for theorizing about technological transitions.

We wanted to examine how various constituents justified or resisted the leap to the next generation technologies and what happened during the interim period between successive technological generations. These constituents mainly included competing firms (mobile network operators, manufacturers and infrastructure providers), regulatory agencies (Office of Telecommunication (OFTEL), the State and financial, infomediaries (media, analysts, investment banks and consultants) and special interest groups such as environmentalists.

Data sources

Data concerning the actions of all these constituents were acquired primarily through three sources. First, we interviewed several key executives in many of the firms who were involved in adopting the third generation technologies or who chose not to adopt it. Similarly, executives in financial and other intermediaries who served in advisory positions to participating firms were interviewed regarding their role in this migratory process. Second, we also participated in several conferences well attended by key decision-makers representing all stakeholders in the field. Third, we carried out an exhaustive survey of archival material and downloaded all relevant articles from 1997 to 2005 from a number of publications sensitized by out study (e.g. Financial Times, and The Economist) and trade magazines (e.g. Wireless Review, Wireless News). We accessed data from company websites, internal reports, analyst reports on mobile data, operators strategies, 2G, 2.5G and 3G mobile communications (e.g. from Credit Suisse First Boston, Lehman Brothers, and HSBC), dedicated websites (e.g. www.telecom.com, 3Gnews.co.uk, Zdnetuk.co.uk), online databases (e.g. Lexis-Nexis, Reuters) and scholarly journal articles. We also accessed press releases, white papers, reports and articles pertaining to 2G and 3G technologies from regulatory agencies such as the UK telecommunication regulatory agency Ofcom, the Universal Mobile Telecommunications Services (UMTS) forum (an organization representing the industry, regulators and other government institutions), OMA (Open Mobile Alliance) (consisting of more than 300 companies representing mobile operators, device and network suppliers, information technology companies, and content providers) and telecom consultancy companies. Finally, we read and took notes from several books on mobile telephony's various technical as well as socio-economic aspects.

Data analysis

We systematically analyzed this data using a narrative approach (Pentland, 1999; Van de Ven & Poole, 2005). Specifically, we first recounted the surface level details based on an analysis of salient events that unfolded (Miles & Huberman, 1994). Then, we examined the underlying driving forces, paying specific attention to contradictory forces for momentum and inertia (Tsoukas, 1989). Our analysis helped us make sense of what happens in a network as these contradictory forces for momentum and inertia clash over time across the network. Using the Nud*Ist 4 software, we first coded the data, where we assign labels to text units (sentences or paragraphs in a coding procedure) (Miles & Huberman, 1994; Strauss & Corbin, 1998). After we identified potential categories, we grouped the initial codes into a smaller number of aggregated themes (cf. Miles & Huberman, 1994) in order to understand the underlying patterns. By systematically analyzing all interview transcripts and archival documents, we identified a series of patterns, vis-à-vis the forces of momentum and inertia. A systematic process of data reduction allowed us to identify the most relevant issues in our data and develop a valid and reliable narrative (Miles & Huberman, 1994; Strauss & Corbin, 1998).

TECHNOGICAL EVOLUTION IN MOBILE COMMUNICATIONS

On April 19, 2000, the UK government held the first 3G spectrum auctions in Europe, raising an unprecedented $35 billion from the sale of five licenses. Soon thereafter, the spectrum auction in Germany raised almost $50 billion. While subsequent auction proceeds from spectrum auctions in Europe did not reach such surreal levels, the combined revenues from the sale of licenses for 3G mobile technologies raised more than $100 billion as many mobile operators made their biggest ever investments. The timing of the auctions had coincided with the peak of the dotcom boom that had not only made these investments seem justifiable at the time but had also allowed access to ‘easy money’ from willing lenders.

Five years down the road, the demand for products and services based on 3G technologies remained well below expectations. Many were convinced that the enormous prices paid to obtain these licenses were completely unrealistic as far as the potential for future profits was concerned, and that firms were saddled with the winner’s curse (Kagel & Levin, 1986). Indeed, even just after their completion, the auctions were variously described as the ‘wireless gamble' (The Economist, 2000) and a 'spectrum land grab' for a new and untried technology. Many mobile operators delayed rolling out infrastructure for 3G systems and wrote down the value of their spectrum licenses while some even returned these to the state at considerable loss. Despite the tremendous optimism that the third generation mobile technologies had generated at the turn of the millennium, lack of interest from end users kept penetration rates extremely low. Even by 2005, out of the almost 2 billion mobile customers worldwide, just about 2% had migrated to 3G systems and even those customers sparingly used the various 3G services. See table 1 for subscriber numbers for the various technological generations.

-- Insert table 1 about here --

In the wake of such low demand for the new technology, many operators decided to focus on upgrading the previous generation 2G systems to what came to be known as 2.5G. This interim 'solution' provided almost all of the benefits that 3G had promised, yet at a fraction of the cost and without the need for costly new spectrum licenses. As the label 2.5G suggests, instead of a smooth transition from the second to the third generation, the system settled down somewhere in between, incorporating facets from both generations. To understand how and why this happened, we need to look far beyond the technologies at play. A richer understanding would entail studying the various constituents of the entire ecosystem in which the technologies are embedded (Adner, 2006; Van de Ven and Garud, 1993; Geels, 2002). We describe such an ecosystem for the mobile communications industry.

The Mobile Ecosystem

At the time of the auction, the mobile ecosystem, including handsets and other co-specialized assets, was locked into a 2G mode that had reached saturation levels of penetration. For a new technological system like 3G to work, it would require not only new core and complementary technologies but also several co-specialized assets (Teece, 1986). These assets include, for instance, new generation handsets from manufacturers (that are also compatible with previous generation mobile phones), new base stations and masts from infrastructure providers for the transmission of 3G signals and compelling ‘content’ (video games, websites etc. for mobile handsets) from application developers. As the competences of mobile firms operating under 2G were limited to providing voice-based services, they had to enroll a wide range of stakeholders, such as banks and entertainment companies to develop new kinds of services – mobile banking and purchasing, interactive video games on the mobile etc.

Since spectrum is a state-controlled resource, the ecosystem also involved regulators. Similarly, infomediaries – analysts and media – also played an important role. Besides, environmental groups concerned about the potential radiation hazards from 3G systems were important social groups influencing the transition process.[4] This social group urged municipalities to resist allotting building permits for new sites for 3G transmitters. Finally, any technological ecosystem will remain isolated without a critical mass of users who attach various meanings to products, vis-à-vis their value in use. For 3G to become viable, end users would have to show an interest in using 3G services. Before we elaborate further on the roles of various actors in the mobile ecosystem, we first provide a brief overview of the essential characteristics of 3G technologies and the advantages it promised over the preceding 2G systems.

Key Characteristics of the Third Generation (3G) Wireless Technology

As against the globally dominant GSM (Global System Mobile) standard in 2G technologies, 3G technologies used the CDMA (Code division multiple access) radio interface

[4] 3G systems operate at higher frequencies that required the construction of additional masts and base stations in cities as well as more powerful handsets than 2G technologies. Many believe that these components posed significant radiation hazards.

standard. CDMA is far more efficient in 'farming' available spectrum space by assigning a unique *code* for each frequency channel, thereby providing more traffic per megahertz of spectrum (Funk & Methe, 2001). Most 2G technologies, including the European-led GSM standard, was based on TDMA (Time division multiple access) – a technology that creates multiple access channels for subscribers by *spacing* frequencies in time.[5] 3G systems not only made more efficient use of spectrum but also had the capability to transmit large amount of data at much higher speeds by using a bigger band of spectrum as compared to 2G. As against 14.4 kilo bytes per second (kbps) 3G could transmit data at up to 2000 kbps.

Besides these differences in the core technologies surrounding the two generations, 3G also offered a more efficient way of transmitting wireless data. All third generation technologies use 'packet based' systems for sending data – a technology employed in the Internet. At the time of originating a data file's transmission, the file is split up into smaller units, or packets, containing identifiable information, which is needed for their re-assembly at the file's destination. Available bandwidth usage is optimized by minimizing the transmission 'latency' (i.e. the time it takes for data to pass across the network). In contrast, 2G technologies use circuit-switched technology that sets up a dedicated connection between two callers for the entire duration of the communication. Even if no actual communication is taking place, the channel still remains unavailable to other users, creating inefficiencies in spectrum utilization.

While the core 3G technology, CDMA, along with the use of packet switching for data transfers allow better utilization of spectrum, the need to handle large amounts of data also need higher spectrum capacity or bandwidth. Spectrum being a valuable resource meant that operators

[5] One exception was the use of CDMA in incumbent 2G systems, such as the CDMA-One (IS-95) that used 2G spectrum. However, with the TDMA-based GSM being the de facto global standard for 2G, the use of CDMA-One remained largely limited to North America (Funk & Methe, 2001).

had to pay billions of dollars just for obtaining spectrum licenses for 3G systems, let alone build technological infrastructure and market the new technology. To understand the exorbitant prices paid for 3G licenses during many of the auctions, we need to look at the antecedents to the 3G auctions. This includes the context in which the auctions took place and the activities of various constituents in the run up to the auctions.

The Enabling Context

Actors respond to the wider socio-economic conditions that form the institutional context from which new practices emerge (Dobbin, 1994; North, 1990). In the mobile field, the auctions for spectrum licenses in Europe took place amid a dotcom boom and a digital revolution. Technological convergence and a chain reaction of mega telecom mergers made it relatively easy for mobile technology firms to raise money in capital markets. For instance, in early 2000, Vodafone, the British operator at the top end of its market capitalization, had completed the biggest-ever acquisition of the German operator, Mannesmann, valued at over $163 billion.

In such a 'broadband' based environment, one with ever increasing need for bandwidth, many felt that the functionality offered by 2G wireless would not be enough. It is in this context that 3G wireless was proposed, promising the functionality required to seamlessly surf the web on mobile phones. Since almost everyone owned a mobile phone, 3G would make the Internet mainstream and widely accessible by eliminating the need for users to own expensive laptops and PCs (The Economist, 2004b). Furthermore, 3G was seen as a platform that could spur demand for online shopping (e-commerce) by enabling online purchases through the mobile phone (m-commerce). In early 2000, Jeff Bezos of Amazon, the leading online retailer, described m-commerce as "the most fantastic thing that a time-starved world has ever seen" that would change the way people shop, making impulse purchases anywhere, at any time (The Economist, 2001). In the wake of such an expected bonanza, switching to 3G was seen as the most viable growth strategy for mobile operators who widely agreed that the old 2G technology had reached its natural performance limit (Foster, 1986; Sahal, 1985).

Firms' Reasons for Switching to 3G

The end of the voice-based mobile boom[6] (Sammut-Bonnici, 2005) meant that revenues from traditional voice-based telephony had reached almost saturation levels and there was little scope in adding more users to the network. The only way to grow, then, was to increase the *usage* of the network or the ARPU (Average Revenue per User). 3G was expected to create a huge surge in revenues from data-based services that would require much greater bandwidth than what the existing, overburdened 2G systems were capable of delivering. Eager to tap new sources of revenues, it seemed logical for mobile operators to bid for additional spectrum space and obtain licenses for switching to the third generation.

Besides the perceived expectation of an imminent decline in traditional 2G services, there were several other reasons for firms' decision to migrate to 3G. First, as discussed above, in the wake of the buoyant sentiment at the time of the auctions, the financial markets had a very optimistic appraisal of the telecom market's prospects and were expected to reward firms that made this transition. Eager shareholders of mobile firms thus exerted considerable pressure on management to acquire 3G licenses. An executive in the UK stated that given the market sentiment, it was almost "unthinkable" to be left out of the race (for 3G licenses).

> "We had to buy this license for 'defensive reasons' A financial market related factor is how much of a hit you take on your share values, if you don't get the license that would far outweigh the price that you have actually paid for the license. At the end of the day a debt of £4 billion (price of 3G license, the firm acquired in UK) is massive but if your share price drops 40% it's a lot more than

[6] The creation of a European-led dominant global mobile standard has resulted in phenomenal growth rates in mobile telephony, with an average rate of over 60% from 1995 to 2000.

> £4 billion….The market was so bullish and so keen on 3G that, either you die instantly if you don't get it or you die slowly if you do get it.….. We started with a business plan like everybody else and then ended up, throwing it in the trashcan." (Senior executive from mobile firm, Orange)

Second, as 3G promised a single, unified global standard[7], the temptation to create viable global 'footprint' was huge. This required a license at multiple locations as firms hoped to build sufficient size and scale to drive not just pan-European but global branding with seamless international networking. Firms also hoped to achieve higher bargaining power with equipment suppliers, especially of handsets.[8]

Third, with 3G mobile, operators could "monetize the Internet" and earn revenues through web-based services[9] (The Economist, 2001). Mobile operators believed that they had an important advantage over Internet service providers and fixed line companies in providing Internet services. As an interviewee stated:

> "I think the mobile operator with the capability to bill for telephony but also for 'service packages,' has a big advantage over Internet service providers with no direct billing relationships and even the fixed operators who normally bill a home or an enterprise, rather than an employee or a person" (MD of Hutchison, UK).

While there seemed several compelling reasons for firms to invest in 3G, several other actors played an important role in 'hyping up' 3G in the run up to the auctions. We discuss the role of these constituents that include equipment manufacturers, regulators, analysts and media in fuelling firm optimism for the new technology.

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[7] The regulators wanted to avoid the patterns of global fragmentation that had characterized the market during the first and second generations with North America, Japan, and Europe retreating into separate camps. This resulted in an isolated, balkanized landscape of incompatible technologies, especially in the US.

[8] Operators normally subsidize handsets sold to their customers and therefore need favourable financing terms on network equipment from equipment providers.

[9] Internet service providers face major challenges in making money from web-based services (news, weather reports etc.) that are mostly 'free,' given that most do not enjoy direct billing relationships with end customers. Mobile operators in contrast were in a unique position to charge for such information.

Support from other Constituents

Equipment manufacturers were eager that mobile operators make the switch to 3G given its perceived potential. With their 2G product lines nearing obsolescence, manufactures, such as Nokia and Ericsson, stood to benefit considerably from the development of the 3G market. Indeed these companies were the first to come up with the term ‘3G’ to describe the technologies as a new generation.

Our analysis of most official reports suggests that regulators also had strong motivations to raise optimism about 3G. The reason to support 3G was to develop a European-led global standard and maintain Europe’s lead in mobile communications. 3G was also expected to benefit the economy by generating new business ventures and jobs and unleashing a wave of secondary innovations through the convergence of media, telephony and Internet computing. Indeed our review of the reports on the governments’ decision to designate 3G spectrum indicated a strong bias in favor of the new technology. Regulators were also driven by the prospect of receiving a windfall for the national exchequer through auction proceeds. Despite the “large uncertainty” about the size of demand for 3G services, the price elasticity and the nature of competition in future UMTS (3G) markets, these reports painted an optimistic scenario for 3G as a technology (Borgers & Dustmann, 2003: 228). We provide an example of the UK where the first and most lucrative auction took place. Reports from Ovum Ltd and Quotient Communications Ltd (1998) based their analysis on the figures for London – UK’s largest city with a dense network and heaviest usage of mobile services (Borgers & Dustmann, 2003: 229-230). London was chosen so as to ensure that the demand for 3G services would not be underestimated. Most consultancies also presented an optimistic scenario, concluding that early users of 3G services would be relatively ‘insensitive’ to cost and that demand would be *independent* of price considerations (Communicator, 1999: 6).

That the state regulators were interested in maximizing revenues from spectrum licenses is also evident in the time and effort they dedicated to an effective auction design. In the UK – the venue for the first 3G auction in Europe – the state hired renowned academics who designed a revenue-maximizing Anglo Dutch design. Furthermore, the government engaged in a sustained marketing campaign to attract entrants (Binmore & Klemperer, 2002), describing the technology as truly “revolutionary.” The following quote from UK officials represent the state’s attempts at creating a favorable impression about 3G.

> “Third Generation (3G) mobile technology will transform how we access information, creating applications and opportunities, we are only beginning to imagine. Along with Interactive TV, it will bring the Internet to people who would never dream of having a computer at home.” (Patricia Hewitt, Small Business and E-Commerce Minister, quoted in Financial Times, 1999)

Finally, another strong indication of the UK government’s interest in maximizing auction proceeds and generating momentum for 3G was the rather fortuitous timing of the *Stewart Report* on the potential hazardous effects of using mobile phones. This state-commissioned report was released exactly *one* day after the auction was completed. All the managers we interviewed for our study confirmed that had the report been released earlier it would have had a dampening effect on the prices.

While the regulators played a strong role in generating momentum for 3G systems, our data suggest that infomediaries such as investment bankers, mutual funds, and other investors in telecommunications also upped the 3G ante and linked the ratings of the telecommunication companies to their engagement in 3G projects. Having severely underestimated the tremendous growth during the second generation, many analysts were keen to atone for the mistake. For instance, in a market research report for AT&T during the first generation (mid-1980s), the consulting firm McKinsey had concluded that the cell phone market was not a profitable option, as the worldwide market potential would be only around 900,000 at the turn of the millennium (Economist, 1999). However, the actual number of cellular phones in the year 2000 was in excess of 400 million globally.

Given such gross underestimations in the past and in view of the buoyant market sentiment at the time of the auction bidding, security analysts, not surprisingly also found themselves under tremendous pressure to come up with optimistic estimations of the 3G market. In many cases, completely new ways of framing the license's potential were devised by advisors in order to justify the high prices being paid by clients. For instance, in their 2001 report on the UK license winner, Orange, HSBC claimed that the initial forecasts for the prices of spectrum licenses were vastly "underestimated" because bidders were looking at the license from an "overlay" perspective rather than a "holistic" view. From an overlay perspective, the report argued, 3G services were treated as just one layer of additional services rather than a leap for the entire mobile market (HSBC Report, 2001).

The press also jumped on the bandwagon to generate favorable attitudes about the new technologies' potential, portraying 3G mobile telephony as a gigantic shift in the way people communicated with each other. For instance, it was noted how "the telephone will be an intelligent universal gadget that we use far more for shopping, video-conferencing and watching video than for making voice calls" (Daily Telegraph, 1999). The following quote is another example.

> "3G will be on a different plane. For starters, the data rate is phenomenal – 2M bytes per second if you are in a 'cell' close to a transmitter, or 384k bytes for normal mobile use. At that rate, videophones become an everyday reality, along with television and radio on

demand and multimedia Internet content surpassing anything available to the average consumer today" (Sunday Times, 1999)."

The 3G Spectrum Auction

Collectively, the interrelated constituents and the various social groups comprising the mobile ecosystem generated tremendous optimism for the new technology, just prior to the spectrum auctions. It was no wonder that the industry leapt at the chance to get a piece of the spectrum when the governments designated a specific bandwidth and put up licenses for sale in 2000-2001. Overall, European operators invested over 110 billion Euros in what was one of the biggest investments in recorded history by any industry on the introduction of a new technology.[10] In comparison, the license fee from 1994-2002 for 2G spectrum was in the range of just 10 billion Euros for the entire European market. In the case of 3G, just in the UK auction for instance – the first to be held in Europe raised about $35 billion from selling 5 licenses – 4,000% higher than the minimum price set by the UK government (Borgers & Dustmann, 2001).[11] The UK auction recorded the highest revenues in part because of its Anglo-Dutch design – a hybrid – that could capture the virtues of both the ascending (English) and sealed-bid (Dutch) forms (Klemperer, 2002). In this design, the auctioneer begins by running an ascending auction until just two bidders are willing to pay the current price. The two are then each required to make a 'best and final' sealed-bid offer and the winner pays his bid. This format reduces the

[10] While auctioning spectra licenses was unprecedented in Europe, the regulators in charge of 3G licenses had taken a cue from the spectacular success of spectrum auctions in the US. The US regulator, Federal Communications Commission (FCC) had raised an astonishing $42 billion between 1994 and 2000, described as the "49 California gold rush" (Business Week, 1993). Also, some countries such as Japan and Sweden had decided to stick with the format of using administrative mechanisms (beauty contests) for allocating 3G licenses, as had been the case during the previous generations of mobile telephony, when these licenses were simply awarded to 'deserving' firms.

[11] While almost every incumbent operator bid for a 3G licenses, a notable exception was the French firm, Bouygues. Its CEO, despite intense pressures to make a switch to 3G chose not to apply for a license. He was later vindicated when the French government slashed license fees and the operator obtained a license at less than a quarter of the original license fee (Baker & Clifford, 2002).

incentives for firms to form consortia prior to the bidding, as they can be beaten in the final round. It also makes tacit collusion harder, because the sealed-bid stage allows firms to renege on any tacit deals without fear of retaliation.

The high prices were paid despite the stringent rollout obligations attached to spectrum licenses. For instance, the UK regulators imposed rollout obligations with the condition that 3G services by each licensee were to cover at least 80% of the UK population by the end of 2007 (The Information Memorandum, Ofcom, 2000). As 3G required a completely new infrastructure, meeting this obligation in sparse demographic distributions and terrain (providing coverage to the 'last mile') would require huge further investments in addition to the payment for licenses. The total projected investment for rolling out 3G network infrastructure from 2001-2010 in Europe was about another 250 billion Euros. Mobile firms nevertheless made huge investments in their commitment to 3G despite these tough license requirements.

The Auction Aftermath

More than five years down the road, the migration had not occurred as intended despite a concerted effort at 'technological push' from many operators. Analysts forecast at the time of the auctions had been that the technology would be up and running by 2003-2004 and generate significant rents by 2005. Even at the end of 2005, 3G penetration levels remained almost insignificant. In terms of market share, out of the almost 2 billion mobile customers worldwide, just about 2% were on 3G systems and even these customers sparingly used the various 3G services. It still remained unclear which type of 3G data services would utilize the excess capacity and be popular with end-users.

Given such low diffusion rates, an increasing number of mobile firms had to scale back their targets, withdraw from unattractive markets, and delay or even abandon 3G rollouts. The enormous sums spent at the auctions, now seemed an extremely unwise investment. The Financial Times summed up the situation in these words: “Taking into account the write-offs, bankruptcies and closures worldwide, probably $1,000 billion has gone up in smoke” (Financial Times, 2001). With customers evincing little interest, and most analysts and investors increasingly skeptical about 3G, the future of the technology looked far from bright. Even some of the mobile operators that had invested billions began to express doubts about the economic viability of 3G. This was evident when the chief executive of BT Cellnet, Peter Erskine stated: “There is recognition that too much was paid for 3G licenses.”

3G’s Stumble

Several forces were in play to retard the evolution of the mobile ecosystem after the auction. These included the changed macro context and the activities of several actors that held back the transition to 3G systems. The end of the millennium saw the dotcom crash and the start of what could be described as a ‘technological implosion’ that severely dented confidence in new technologies. The investments that had seemed prudent in 2000 now seemed excessive. While, ex ante, the mobile operators had been very eager to acquire spectrum licenses and make the transition to a ‘superior’ and potentially more lucrative technology, they found it increasingly difficult to make further resource commitments to 3G. This held back the technology’s progress. We explain some of these effects below.

Resource constraints. Resource constraints arose from two factors. First, having made enormous investments for licenses, firms were financially constrained. Second, with the increasing reluctance of financial institutions to lend more to an already embattled sector, funds to build new 3G infrastructure were in short supply. To make matters worse, the investment and operating costs for a 3G network infrastructure turned out to be much higher than initial projections (European Commission, 2002) that put further strain on firm resources. Not surprisingly, several firms that received a license have decided to postpone or even abandon the building of the network infrastructure, in violation of their regulatory commitments. Other firms decided to simply hand back the license to the regulator, even foregoing the high license fee. Even when they held on to the licenses they had acquired at huge prices, many wrote down their value. A European operator, mmO2 wrote down the value of its 3G investments by nearly $10 billion while KPN – the Dutch carrier wrote down about US$ 9 billion from 3G licenses. While firms were responsible for delays or even an abandonment of 3G rollouts, end users evinced little interest in the 3G services that were being offered. This generated negative consumption externalities that further retarded 3G's progress.

The role of users and negative consumption externalities. The demand for 3G services turned out to be dramatically below expectations with inability on the part of the mobile industry to inspire their consumers with the added features and functionalities of the new technology. The vice-president for mobile software at Nokia noted: "The industry has not been looking at the user. It's been looking at its own navel" (Baker & Clifford, 2002).

Most research indicated that people were still limiting their use of the mobile for 'person-to-person' social communication as against third party 'broadcasting' of content (such as listening to news) that 3G had promised. Indeed, social communication (speech and text messaging) still account for almost 98% of revenues. In a recent Harris Interactive survey, 44 per cent of respondents said they would not use their mobile phones other than to make ordinary calls. In fact about 52 per cent of those questioned did not even understand what 3G stood for.

Furthermore, the low demand for 3G services generated negative consumption externalities. Since the customer demand for new services was dependent on complementary assets such as compatible handsets and the content developed for the network (i.e., the software for say mobile banking that had to be written exclusively for 3G mobile handsets rather than PCs or laptops), delays and glitches were sure to retard 3G's adoption. However, given the slow uptake and small 3G user base, equipment manufacturers and software developers had little incentive to make rapid investments. The UK head of Hutchison 3G, a new entrant and the first to launch 3G in the UK complained of a lack of handsets that slowed down the penetration rates. As a respondent noted:

> "Heavy handsets with low battery life did not help our cause…… Nokia (the leading manufacturer) adopted a wait and see policy for investing in 3G handsets and delayed deliveries that severely disrupted our operations" (Managing Director of Hutchison 3G, UK).

Lack of complementary investments in turn, stalled the development and diffusion of the new technology. Being already under tremendous financial constraints and with little new revenues from 3G services, firms were not in a position to appropriately invest in marketing 3G as a service and gain end-user acceptance. This created a vicious cycle that held back the mobile ecosystem.

Besides resource-constrained firms and indifferent end-users, the infomediaries also contributed to retarding 3G's adoption. Most analysts and the media that that had upped the ante for the new technology ex ante, had now turned decisively against 3G. Furthermore, 3G faced resistance from environmental groups and was also threatened by the development of substitute technologies. We elaborate on these below.

The role other constituents. Analysts that had hyped up the new technology at the time of spectrum auctions now started to speak of much longer (up to 30 years) payback periods for 3G investments and opined that firms had exposed themselves to a high risk of premature technology introduction. There were many ex post rationalizations that firms had overpaid for

3G licenses. A research analyst drew an analogy with the dotcom boom, stating: “As regards pure dotcom businesses, many did not have any forecast in the real meaning of the word. Drawing a take-up curve without any supporting research is not a forecast, but wishful thinking. Telecom companies, in their eagerness for a license, forgot these basic principles.” He further added “with just a few numbers it was clear that the 3G bids were beyond reality!” The only way the bidding teams could justify these new bid prices to their companies was to change their revenue forecasts and move them into unreal territory.”

Another analyst argued that mobile firms had made a fundamental error in judging the demand for 3G services. The 3G value chain is different from earlier generation mobile phone markets. While 3G provided mobile access to the Internet, the demand for that access is “derived’ from the demand for services delivered over the Internet. This was unlike the previous voice-focused networks (1G and 2G), in which demand was “intrinsic” to the mobile networks. For the Internet, no license was required to provide content and neither could a mobile operator get away by restricting access to such content (Ure, 2000).

Not surprisingly, the media that had vociferously supported 3G just prior to the auctions did a *volte-face*. While there were hardly any articles, exhorting caution at the time of the auction, there has since been a relentless spate of material about the auction being a gamble and “a game of poker,’ with 3G “Universal Mobile Telecommunication Services” (UMTS) being labeled as “Unproven Market, Technology and Services.” Even some national governments echoed the pessimistic scenario, with the Finnish minister of transport and communications calling 3G auctions “the biggest industrial political failure since the Second Word War” (Klemperer, 2002).

While the infomediaries played a major role in dampening 3G's prospects, there was also resistance from a number of environmental groups. These groups put up strong resistance to the building of the much needed new base stations and 3G masts (transmitters), in view of their perceived link with radiation hazards. Finally, to make matters worse, a number of alternative technologies cast a long shadow over the prospects of 3G. One of these alternatives was Wireless Fidelity (WiFi) that could siphon data traffic away from 3G networks by providing mobile information access in designated locations, known as 'hotspots.' While at this stage, hotspots were limited to airports, coffee shops, or universities, there was speculation in the industry that in the near future, all the hotspots could be linked together to create a seamless universe for all users. It was even feared that rather than generating new sources of revenue as was originally expected, 3G technology could end up merely as a way for mobile operators to boost their capacity for traditional *voice* calls in the overloaded parts of their 2G networks (The Economist, 2001). In short, 3G was no longer regarded as a paradigm shift in mobile communications that would open up a goldmine of new revenues for mobile operators.

It is important to point out here that 3G licenses were not a pre-requisite to be a player in the mobile telephony market. Indeed, many industry experts argued that 3G technologies were not a dramatic technological breakthrough but simply a new domain of application (Levinthal, 1998). Thus, while incumbents feared the loss of their existing mobile franchise if they failed at migrating to 3G, the situation was not *fait accompli*. Having leaped forward to embrace 3G, it soon became apparent that the industry could no longer count on the new generation technology for their future survival and growth. Many firms in the industry thus decided to 'backpedal' by stretching the capacity of the old 2G technology (Sammut-Bonnici, 2005).

Extension of the Old Technology

2G was upgraded to what came to be known as two-and-a-half generation (2.5G) or GPRS (General Packet Radio Services) through bolting on packet-switching data transmission technology onto 2G systems. Sometimes called '3G-lite' in the industry, these 2.5G upgrades essentially allowed faster connections to the internet via the mobile phone. 2.5G could handle data transmission speeds between 33.6 and 128 Kbps, as against a maximum of 2000kbps for 3G, thereby lifting the performance to a level which is in the middle range of 2G and 3G. Thus, while 2.5G marked a significant improvement in 2G systems, it nevertheless operated on the limited 2G spectrum and did not achieve what 3G was capable of. As an example; downloading a song with a 2.5G network would take over a minute as against 5 seconds on a 3G network.

As the mobile ecosystem seemed to temporarily settle down around 2.5G technologies, a number of mobile firms with 3G licenses, such as Vodafone, delayed their 3G launches beyond initial promises and focused on upgrading their 2G networks to 2.5G. Firms without 3G licenses, such as the Danish operators, Sonofon and Telias also decided to focus on 2.5G and offer most of what were supposed to be '3G' services. Many operators now acknowledged that the much-hyped transition to 3G was unlikely to be momentous and began to regard 3G as *evolutionary* instead of revolutionary. Indeed, as Dave McGlade, CEO of BT Cellnet (later known as mmO_2) stated in 2003: "In terms of the kinds of applications our customers are going to use, I don't think there is a huge difference between 2.5G and 3G" (Telecom Review – Conference proceedings in the 3GSM World Congress in 2003).

While many operators chose the 2.5G route, they faced a dilemma – preventing the cannibalization of their customer base network in a near-saturated market while, at the same time, also requiring them to sign up for new expensive 3G contracts to increase the ARPU. The situation actually was far more complex than having to decide between two rival basic technologies. According to Bob Merritt, VP of Semico Research Corp. “It is going to be a case of supporting 2G, 2.5G and 3G, all at the same time. This isn’t going to be a nice, smooth transition.”

Worse still, was the prospect that firms that chose to upgrade to 2.5G could bypass 3G and make a direct leap for 4G (The Economist, 2003). These 4G system were expected to include new technologies such as improved modulation that could deliver full motion video on mobile devices. A former high ranking objective of a major mobile operator we interviewed suggested that 3G could well be a “stillborn” technology and the third generation a “lost generation” (Former head of technology of NTL, the second largest telecom in UK). Thus, it was conceivable that 3G could simply be leapfrogged by what was being labeled as 4G. Figure 1 depicts the development of performance for mobile technologies from 1G to 4G (projected) where each technology is introduced at a higher performance level than the former technology.

-- Insert Figure 1 about here --

FINDINGS

Our intent was to understand the micro dynamics during the period between technological transitions as ex-post representations miss out on intermediary processes. These processes go far beyond the technologies at stake. Consequently, we examined the actions, interests and preferences of various social groups in the context of a generational shift in mobile communications.

The transition from one generation to another within an ecosystem is often characterized by pulls that facilitate or impede transitions. These pulls can include a technological force (supply-side), a market force (demand-side) and pressures from various institutional players (infomediaries, regulators), the combined effect of which can generate both momentum and inertia. We discuss how these forces played out at various levels and stages of the technology's evolution.

Momentum for the New Technology

Since additional spectrum was a prerequisite for migrating to the next generation technology, mobile firms had to acquire the rights to use it through purchase of licenses at considerable costs in most cases. In the context of a dotcom boom, a digital revolution and eager investors for anything hi-tech, firms collectively spent over $100 Euros for acquiring these licenses and migrating to the next technological phase.

Several forces led to the collective exuberance for actors eager to climb on the 3G bandwagon. Mobile firms widely believed that 2G had reached the end of its tether and, that, without 3G, the industry would be at a serious disadvantage in serving future customer needs. At the same time, through designating a specific time and allocating a particular bandwidth for 3G spectrum, national regulators in effect imposed a single expensive technology that all countries in Europe needed to collectively adopt. In addition, the "one-off" character of the spectrum allocation process had created a 'now or never' mindset - there would not be a second chance to obtain a 3G license in a reasonable time period. This created a prisoner's dilemma for incumbent operators as despite staggering license costs, 3G seemed the only route to safeguard their installed customer base (2G).

The firms' belief in the new technology's potential was reinforced by various other constituents, such as the media and analysts through sketching utopian future worlds (Rao et al., 2001). Parts of this rhetoric were the various self-reinforcing and mutually dependent forecasts. It was difficult for consultants, analysts and other experts to make 'independent' forecasts because true expertise could not be outsourced. To do their math, the forecasters were dependent on figures from the marketing departments of mobile firms. Excessive differences in forecasts were likely to 'stand out' and it made sense to stay in line with others rather than to offer a contrarian version. Even inside the mobile companies, the more skeptical views from technology people were swamped by the future visions of brand management and finance (Pantzar & Repo, 2005). As the interdependence between analysts' forecasts and firms' actions grew, it further reinforced the most optimistic forecasts. Collectively, these forecasts led to a particular rhetoric around the new technology,

Orchestrating a purposeful rhetoric can lead to a context where managers feel "irrationally exuberant" (Taylor & Brown, 1988), despite objective information. As various constituents up the ante for a new technology's potential, it generates momentum in its favor. Momentum is not just about certain technologies getting locked-in and generating tipping effects through positive consumption externalities that drive their rapid diffusion (e.g. Arthur, 1989). Momentum can also be generated by other constituents such as infomediaries and the state regulators, especially during the initial stages of a technology. For instance, zero emission laws in California have tended to spur growth in alternative automotive technologies such as hybrid engines. Thus momentum exists at various levels and during various stages of a technology's evolution. While certain stages of a technology's evolution can be characterized by momentum, others may exhibit inertia.

Inertia against the New Technology

In the context we studied, the actions of certain constituents in the later stages of the technology's evolution and a dramatic downturn in the market sentiment for new technologies led to penetration levels that were far below initial expectations. While some social groups had contributed to generating momentum for the new technology, others stalled its progression. An important inertial effect was the lack of co-specialized assets. 3G services could only be as good as the content offered on them and 3G handsets were only valuable if they could access compelling high quality content.[12] Without a critical mass, there was little incentive for content providers to develop software and content for 3G or for equipment providers to invest in new generation handsets. On the other hand, without compelling content and quality handsets, 3G services were less likely to achieve critical mass.

Furthermore, in their exuberance for the new technology firms had been culpable of technological 'overshooting' as they had overcommitted resources to what was seen as an extremely promising technology (Gilbert & Bower, 2002), without a careful consideration of customer needs for the added functionalities. A majority of users continued to use the mobile phone for simple calls and text messages rather than sophisticated services such as making online purchases. Even video telephony – the only application exclusive to 3G – had failed to achieve customer acceptance.[13]

Customers often retard purchase behavior in anticipation of something better or cheaper to follow (Rosenberg, 1982). They also do not embrace a new technology because there is not yet a critical mass around the new technology (what Farrell and Saloner, 1986 have labeled as the Penguin effect). In the meantime, the old technologies continue improving to a point where consumers' performance requirements are adequately served by an existing technology. The

[12] For instance, the new generation high resolution flat panel and 'High Definition ready' TVs are limited by the poor quality of the currently analog TV signals.

[13] This had been witnessed much earlier on in the case of fixed line telephones. Video phones have been around since the 1960s but never became popular as people did not want surveillance inside their homes (Lynn, Morone & Paulson, 1996).

dynamic is driven by consumers' decreasing marginal returns from performance improvements as the performance of existing technologies, surpass consumers' requirements.

In sum, lack of end user interest, delays in co-specialized assets for the new technology and lack of coordination forced firms to upgrade the previous generation technology. It allowed the system to arrive at an interim resting point that was 'in between' the technological generations. The interim upgrade was a hybrid that bore residual conformity with the old technology while also offering most of the performance attributes of the new technology. Essentially, 2.5G blurred the technological distinctions between 2G and 3G through adding on elements (packet switching) from the new technology. While most industry attention was focused on third generation core technologies such as W-CDMA, it was packet switching (what we label as a "collateral technology") that created a significant enough jump in the existing 2G systems. Indeed, 2.5G systems could serve almost all customer needs without the need for additional investments in costly spectrum licenses, base stations and powerful handsets. Thus, led initially by momentum and later by inertia, the system landed at a point that was in the middle of the old and the new.

DISCUSSION

The body of work on technological transitions has done little to address real-time transition issues at play, such as the forces that arise as a result of interactions between producers, users, and institutional players constituting a technology ecosystem. To develop a richer understanding of the dynamics of technological transitions, we examined recent developments in mobile telephony, focusing in particular, on the interregnum between two successive technological generations, 2G and 3G. As we have observed, the process of technological transition can be messy, erratic and contested, not necessarily driven by smooth shifts; aspects of the past technologies continue to matter; and new technologies with higher functionalities do not simply eliminate the older ones in a process of creative destruction.

In the light of our study of mobile telephony, we have argued for the need to conceptualize networks as a complex ecosystem in order to develop a richer understanding of how transitions unfold. Such as ecosystem includes both social and technical facets and involves a multiplicity of actors such as users, producers and regulators; encompasses forces for both momentum and inertia; and operates asynchronously across different parts in which evolving interdependencies generates adaptive expectations and changes the motivations of the actors involved dynamically over time. We now draw on our findings to develop four conjectures towards developing a richer imagery of technological generations.

Towards a richer understanding of technological transitions

While scholars have discussed the need to take an expanded network or systemic perspective in conceptualizing technological transitions, the various elements of the system are usually seen to be operating in sync as it moves forward from one generation to another (e.g. Hughes, 1983). However, by disaggregating the elements of an ecosystem, we found that, rather than in being sync, the different elements evolved at different rates, thereby setting up the transition to temporal discords. While previous studies have found the existence of either inertia or momentum (Farrell & Saloner, 1986), we found both at various points in the interregnum between successive technological generations. As the mobile communications case shows, these forces change dynamically as the process begins to unravel over time. Emanating from different parts of the ecosystem, these forces may result in exuberance and pessimism at different points in the transition process and cause the system to evolve unevenly rather smoothly or sequentially.

At first, momentum is generated through the optimistic projections that are offered in the form of stories by key actors (Lounsbury & Glynn, 2001). For instance, in the enabling context characterized by the dotcom boom, 'easy money,' mega telecom mergers, and unprecedented growth in mobile telephony, telcos came to believe that the old technology had reached its performance limits and a shift to the new was inevitable. The media and the regulator fuelled this belief further through creating their own stories that hyped up the new technology's potential. Eventually, these firms got caught in a web that they had themselves played a part in spinning. This generated emerging irreversibilities (Callon, 1991), and, being unable to free themselves of the story's obligations, they then began to be shaped by it as they decided to migrate to the new technology (Wagenaar, 1997). Based on this discussion, we offer the following conjecture.

> Conjecture 1: Momentum for a new technology is generated by the actions of not just focal actors, but also by others infomediaries such as regulators and media. Together they create a self fueling prophecy wherein stories offered by focal actors are magnified in the public domain.

However, despite the momentum generated for a new technology at the initial stages, a number of forces can also retard its further development. For instance, delays in the introduction of co-specialized assets required to enable the new technology (a possibility that is likely to arise to the extent that early projections were particularly aggressive in order to attract resources) can significantly influence the transition process. Even as these co-specialized assets are being created, the old technologies may show improvements, thereby reducing the performance gap between the old and the new. Thus delays in the development of co-specialized assets may not only dampen the enthusiasm for the new technology among the various constituents, such as users, but also allow the old technology to close the performance gap with the new. We therefore offer the following conjecture:

> Conjecture 2: A delay in the development of co-specialized assets will make it more likely that the old technology will catch up with the new, thereby reducing

> the performance advantage of the new technology over the old, and, in the process, changing the adaptive expectations of the constituents involved.

It is understandable that a delay in co-specialized and complementary assets makes it more likely that old technology would catch up with the new technology. These improvements may come from within the industry but may also result from developments in related industries. For instance, in the context of mobile communications, a "collateral technology" (the bolting of packet switching onto existing 2G technology) imported from the domain of the Internet appears to have been the true 'radical shift' at a time when most constituents were preoccupied with core 3G technologies. By drawing on elements from the new technologies, this collateral technology created links between different industries – Internet and 2G mobile – and enabled the extension of the previous generation (2G). According to most industry experts, the collateral technology represented a bigger ground shift in mobile communications than core 3G technologies, despite the massive investments that went into developing 3G. Indeed, users did not find 3G to be dramatically different from 2G and most seemed satisfied with upgrades of the old technology that served almost all of their needs. Thus, radical technological advances are not necessarily 'disruptive' for all the constituents of an ecosystem.

The phenomenon of how collateral technologies can revitalize previous generation technologies has been observed in other domains. For instance, improvements in steelmaking from the introduction of open-hearth furnaces in the late 1870's enabled the substitution of earlier generation steam boats for sailing ships. Open hearth furnaces allowed the production of better steel, which in turn enabled boiler plates and boiler tubes to withstand higher pressures. As a result, more efficient steam boats could be operated profitably (Dattee, 2007). Another example of a collateral technology to extend the life of an old technology can be seen with photo-lithography where optical lithography has shown unusual persistence as the dominant manufacturing technology for computer chips since the late 1960s (Henderson, 1995). While the industry was focused on developing “next generation lithography” (NGL) that included technologies such as extreme ultraviolet lithography (EUVL), the discovery of “enhanced liquid immersion” extended the life of optical lithography[14] (Sydow et al., 2007). Infusing optical lithography with a collateral technology required only minor adjustments compared to EUVL for not only extending the path of optical technology but also substantially improving its performance.

In short, collateral innovations in related industries can result in extending the life of the old technology and close its performance gap, vis-à-vis the new technology. Thus, technological developments in related industries also matter in processes of technological transitions. Based on these observations, we offer the following conjecture to be explored in other settings.

> Conjecture 3: Collateral innovations in parallel, related or sub systems can reduce performance gaps between incumbent and new technological systems and thereby prevent any one technological system from emerging as a clear winner.

Any closure in the performance gap between the old and new technologies (because of dynamic forces that we elucidated in conjectures above) again catches the attention of market infomediaries. As we noted earlier, these actors had first helped in generating the hype for the new technology by magnifying the stories that firms themselves provided in support of their strategies (Pollock & Rindova, 2003). Now, with performance slippages, they are the ones to magnify any shortfalls, thereby contributing to inertia. As we saw in the case, the media and several analysts were quick to paint a doomsday scenario for 3G at the first sign of trouble for the new technology. In other words, these informediaries play an important mediating role in

[14] In enhanced liquid immersion lithography (LIL), a drop of fluid (water or oil) is placed between the optical lens and the wafer. Compared to air, the higher refractive index of fluids leads to a better image resolution. Originally used in microscopy to enlarge the image of the specimen, immersion is used in optical lithography to print miniaturized features onto silicon wafers.

generating the excess momentum and inertia that shapes transitions at different points in the process. Based on these observations, we offer the following conjecture to be explored in other settings.

> Conjecture 4: Infomediaries play an important mediating role in creating both excess momentum and excess inertia for the new technology at different times, and consequently, in shaping the transition process.

CONCLUSION

Gaining a deeper understanding of the processes and dynamics whereby transitions between generations occur holds important implications for policy and strategy. In this regard, our paper offers important insights. First, by conceptualizing the journey as involving a multiplicity of heterogeneous elements, we expand the scope of inquiry for the sources of change driving the process. Sponsoring a novel technology involves large upfront investments that can drastically transform the social, economic, and organizational landscapes. With so much at stake, a thorough understanding of the role of multiple constituents and how collateral technologies mediate outcomes in transition dynamics is crucial to firms and policy-makers. Technological evolutions, thus, are not determined simply by a battle between competing technologies. Managers making technology investment decisions need to also pay attention to the interdependencies among various heterogeneous elements in a technology ecosystem, the inter-relatedness and spillovers that may occur among various technologies and the institutional dynamics that surround particular technologies.

Second, our study shows that there is value in disaggregating these elements and in exploring the differential rates at which these elements develop. Such a disaggregation highlights potential temporal discords between the different elements. As the 2G/3G example shows, how these temporal discords play out has a profound impact on the rate and direction of change of the overall system. Specifically, the differential rates at which the new core and co-specialized assets emerge as well as the rates at which existing technologies improve, fueled by speculations by infomediaries such as the media, are parameters to watch out for during the transition process. This observation places a word of caution against unrelenting belief in the supremacy of a novel technology that can render their sponsors "blind with respect to other technological possibilities" (Dosi, 1982: 153), and the prevailing wisdom to abandon old technologies that are sometimes perceived as having reached their natural performance limits. It thus calls for more attention to parallel and complementary developments in both the technical and institutional environments that impact technological transitions.

Future studies in technological evolution should examine multifaceted and complex technological ecosystems in other contexts to gain a better understanding of inter-generational transitions and the dynamics of the intervening period. What are the antecedents of momentum that causes premature jumps to a new technology and what generates inertial forces that stall the migration? When and why do various constituents of the ecosystem evolve at variable rates and what causes them to move in sync? Both fine-grained qualitative accounts as well as large sample quantitative studies can lead to a better theory of technological transitions.

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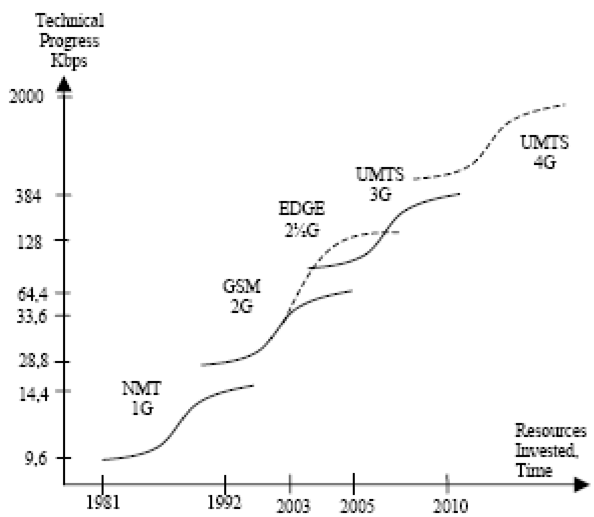
Table 1: Millions of subscribers on 2G and 3G systems

	2002	**2003**	**2004**	**2005**
World	1137.8	1382.9	1714.1	2177.1
GSM(2G)	809.3	1012.0	1296.0	1709.2
Others(1G and 2G and 2.5G)	328.3	368.1	401.3	417.9
3GSM (3G)	0.2	2.8	16.3	50

Figure 1: Neither fish nor fowl but 2 ½ G



2G was upgraded to what came to be known as two-and-a-half generation (2.5G) or GPRS (General Packet Radio Services) through bolting on packet-switching data transmission technology onto 2G systems. Sometimes called '3G-lite' in the industry, these 2.5G upgrades essentially allowed faster connections to the internet via the mobile phone. 2.5G could handle data transmission speeds between 33.6 and 128 Kbps, as against a maximum of 2000kbps for 3G, thereby lifting the performance to a higher level than 2G but well below 3G's performance. As 2.5G operated on the limited 2G spectrum, it could not achieve what 3G was capable of. Nevertheless it was able to close the gap in performance between the two platforms thereby generating increasing inertia to a move to 3G.