Trends and Opportunities for Traffic Engineering Paradigms Across Mobile Cellular Network Generations

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Abstract. Traffic engineering is at the heart of telecommunications engineering. In telecommunication engineering, we have recently experienced a revolution in the form of mobile cellular network generations. History shows a close relationship between the advancements in both telecommunications networks and their corresponding engineering methods. This survey employed qualitative document analysis to chronologically explore the evolution of, and interrelationships between traffic engineering and the mobile cellular networks from 1990s todate. It is evidently a case of the causality dilemma on which of the two influences the other. Neverthelelss,we are currently at the right point in time to make giant leaps in both traffic engineering methods and network technology revolution. This study points out the opportunities that the current state of affairs avails to research in these fields.

Keywords: Teletraffic Engineering · Mobile Cellular Generations · Erlang · Engset. Next Generation Networks

1 Introduction

Traffic engineering (TE) has its roots in voice telephony as a result of groundbreaking work by Erlang [1]. Its usefulness is however still as important in today's telecommunications systems if not more [2]. Although the general objective has remained the same, there are significant changes to how TE is implemented across networks available today. The main objective of TE is to optimize the service demands to the available resources without compromising the service quality [3]. This concept is illustrated in Fig. 1.

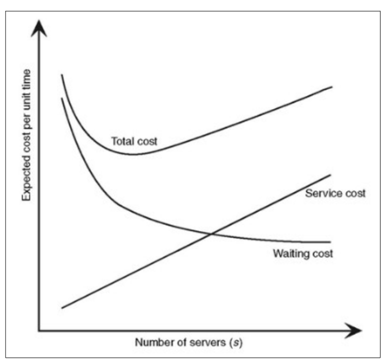


Fig. 1: Network Planning as an Optimization Problem (Source: [1])

Queuing theory is consequently a useful tool that meets the previously mentioned objective in the analysis and design of telecommunication networks [3, 4]. It allows for the analytical determination of the relationships existing among the three aspects of the performance triangle, namely the demand (traffic), the system performance (QoS), and the network capabilities [3]. In the context of telecommunications queues, this field has advanced into a discipline commonly refereed to as teletraffic engineering. Fig. 2 is a summary of the processes involved with emphasis on the relevant timescales of operation within the network.

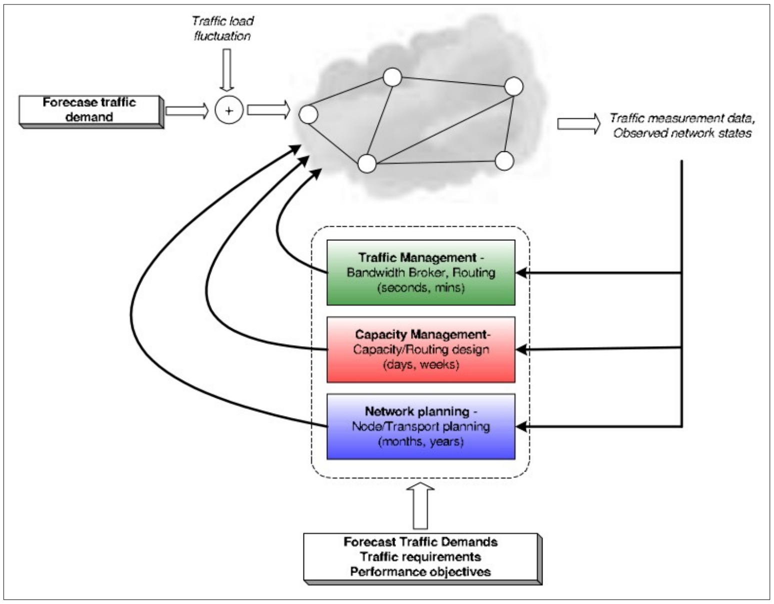


Fig. 2. Traffic engineering concepts and activities (Source: [5])

In mobile cellular networks (MCNs), TE has shown evolution slower than the speed of the deployment of advances in the networks where the most important concerns for network operators have been making wireless transmission possible with adequate coverage [6]. Moreover, value has shifted from service quality to service ubiquity, and this shift together with bureaucracies involved in wireless resource acquisition, has made design with overprovisioning and short term mobile station set ups more lucrative than the trouble of TE.

As a result of the complex relationship between the evolution of mobile cellular technologies and the corresponding shifts in TE paradigms, challenges have kept emerging on both sides. TE concepts, tools and methods have driven technology change at one point, and at a pivotal point in history, technology has taken over, with TE trying to catch up. This is one opportunity where TE can be revolutionized to earn back its reputation as it was during Erlang's era. On the other hand, the extremely fast evolution of technology, higher network capacities and much better network availability signal for a new era in service design and the consequent birth of new usage scenarios. There is also a significant opportunity in the definition of standards in the next generation networks, especially for African standardization organizations which have so far not actively participated in this exercise before. The next killer up is on the horizons.

This paper examines the changes in TE paradigms across mobile cellular network generations, emphasizing on the interrelationship between the changes in TE practices and the cellular generation changes. It attempts to predict possible future directions in both. The study will help to point out opportunities that are available to researchers in these fields.

2 Literature Review

2.1 The Evolution of Mobile Cellular Networks

MCNs have evolved from the first generation analog cellular systems (1G) in 1980s to the anytime, anywhere, any service fifth generation (5G) networks to be launched in 2020 [7]. 1G networks were essentially the PSTN's Wireless Local Loops with mobility. The second generation (2G) saw the now digital MCNs becoming commercially viable, though still predominantly voice centric. The speedy and deep proliferation of connectivity, the demand for better and more demanding services resulted into the data centric, packet switched third generation (3G) of MCNs [7, 8]. In Tanzania, and most other places in Africa, this is the predominant implementation of mobile technology. The fourth generation (4G) brought about even higher data transmission speeds, allowing inter-networking between mobile networks and other wireless access technologies, seamlessly, across multiple, different devices. These capabilities are expected to be even more enhanced in the fifth generation (5G) [7, 8]. Fig. 3 illustrates the evolution of these standards.

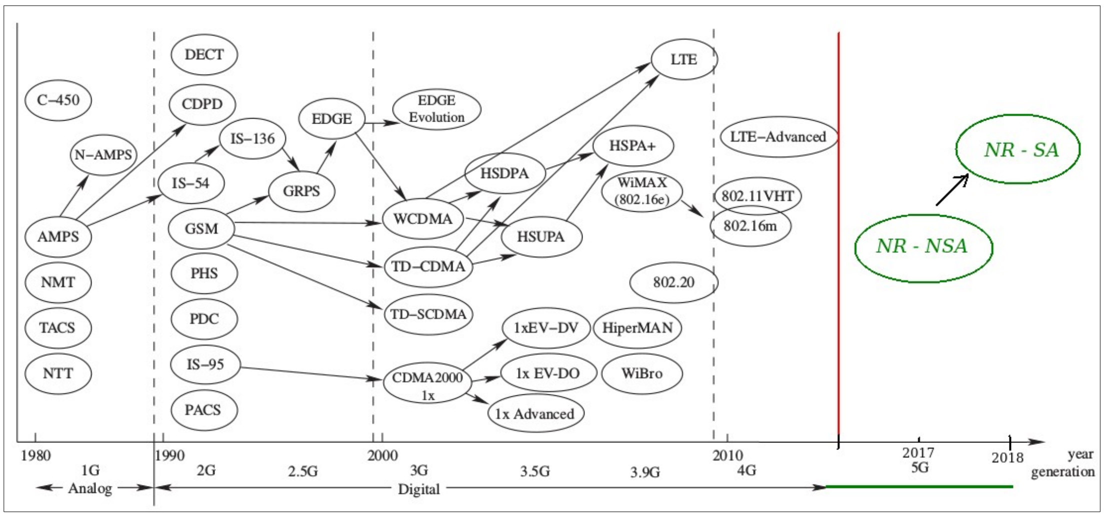


Fig. 3: The Evolution of Mobile Cellular Networks (Source: [7])

Across the generations, one sees a shift from voice centric, to data centric, and potentially, user centric networks. From being circuit switched networks, these networks have also adopted packet switching to accommodate the increasing multimedia, and even hypermedia traffic data traffic. Previously these changes, had been driven by advances in technology, whereas now user demand drives the advances in technology. Table 1 summarizes the important features of the mobile cellular systems across their generations.

Table 1. Salient Features of Mobile Cellular Systems Across Generations (Source: [9, 37]).

Generation	Year	Services	Technology	Speed	Frequency	Description
0G	1960s (pre-cellular wireless system)	Voice only	Mobile radio telephone system	14.4-19.2 Kbps	160 MHz	Large high power cells. No communication away from the boomer cell coverage area
1G (AMPS, NMT)	1980	Voice only	Analog	1-2.4 Kbps	800-900 MHz	Introduction of cellular concept.
2G	1990	Digital Voice	TDMA, CDMA Digital wireless	14-64 Kbps	850-1900 MHz	SMS + voice calls, roaming, call forwarding and call hold introduced, cellular communications commercially

2.5G (GPRS, CDMA 2000)	2000	MMS, Internet	GPRS	115 Kbps	850-1900 MHz	MMS, mobile gaming, access to emails
2.75G (EDGE)	2003	MMS, Internet	EDGE	384 Kbps	850-1900 MHz	Services similar to those of 2.5G
3G (UMTS)	2000	Voice, data, Internet, videos, gaming at high speed	CDMA, Broadband	384 Kbps to 2 Mbps	8-2.5 GHz	Low cost, high data transmission, multimedia services.
3.5G (HSDPA, HSUPA (HSPA 3.6), CDMA EV -DO)	2003	Voice, data, Internet, videos, gaming at high speed	HSDPA	14Mbps	8-2.5 GHz	Services similar to 3G.
3.75G (HSPA+ (HSPA 7.2))	2003	Multimedia and Internet at high speed	HSPA+	84 Mbps	8-2.5 GHz	Services similar to 3G.
3.9G (HSPA 14, LTE)		Multimedia and Internet at high speed	HSPA+	168 Mbps		Services similar to 3G.
4G, 4.5G (LTE – A, LTE - Pro)	2010	Gaming, HD TV, wearable devices, cloud, anywhere web access	LTE, Wi MAX (OFDMA)	100 Mbps to 1Gbps	2-8 GHz	Combined mobile cellular technology with WLAN
5G	2020	web access, Artificial intelligence, remote diagnostics, parallel services, availability of network at high altitudes	IPv6	1-10 Gbps	3-300 GHz	It will provide more device connectivity, less energy usage by the network and more signal efficiency.
Beyond 5G	2030 -	Smart homes, super fast Internet, home automation, Satellite communication, global roaming	Combination of 5G with satellite technology	Expected to be very high (not defined)	Not defined	Possibly roaming even in space

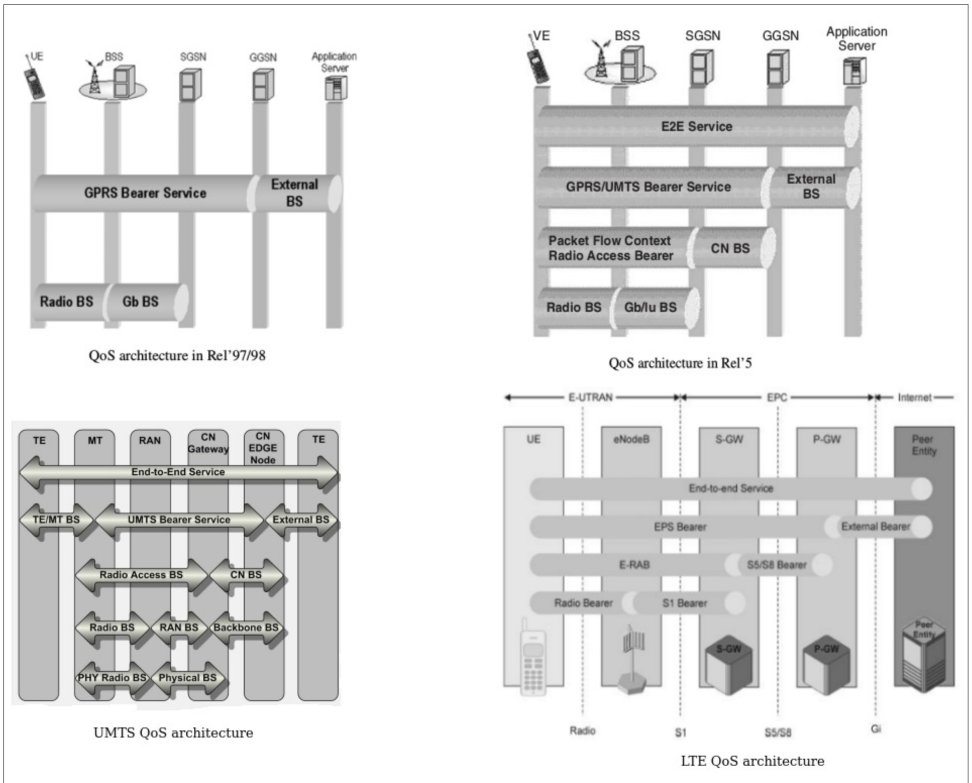
2.2 Traffic Engineering in the Context of Mobile Cellular Networks

Standardization. TE standardization of MCNs has been under ITU – T section, as specified under its E. 750 series of Recommendations. The recommendations specify the physical and logical architectures, as well as high level descriptions of different functionalities. They also stipulate the required performance of the specified technology. The TE recommendations specify different aspects, including how to measure traffic and subsequently characterize traffic as service demand. In addition, the standards specify the GoS and the QoS requirements of the corresponding technology. In MCNs, matching the GoS to the QoS is assured through Service Level Agreements (SLAs). Thereafter, traffic management mechanisms are put in place to make sure that the SLAs are fulfilled. To this end, the recommendations stipulate the traffic control and dimensioning proposals, with emphasis on the radio resources.

Traffic Demand Processes and Prediction. In MCNs the arrival process needs to account for new calls, calls handed over from adjacent cells, as well as calls overflowed to other cell layers in a multi-tiered cell structure. The service time, is no longer necessarily equal to the duration of the call since a call may be serviced over a particular cell for a while and get handed off to an adjacent cell, having released the channel on the first serving cell even before the entire call duration. This aspect makes it important to also model the spatial and temporal behavior of traffic arrivals in addition to the intensity. Whereas previously one could estimate traffic intensity using demographical data alone, it is more accurate now to estimate traffic demand from tracking the individual daily routines, movements and social undertakings; it is all about personal communications.

In earlier generations, fresh traffic arrivals could be safely assumed to be Poisson but with microcells the Poisson estimation underestimates the network performance. Overflow traffic, on the other hand, is super-exponential hence making the Poisson assumption overestimate performance as soon as the overflow traffic is about 10% of the total traffic [13]. Otherwise, in later mobile cellular generations, a mixture of service demands (traffic types) is usually implied, including Poisson fresh calls (random, Erlang), Binomial overflow traffic (smooth, Engset) and Pascal hand over traffic (bursty) [14]. Traffic is characterized by its peakedness as well (variance/mean). Usually in blocking systems, the analysis is insensitive to the distribution of service times which are in turn assumed to be exponential since this definition is important in waiting systems. The traffic streams of different demands are combined by the convolution operation.

QoS and GoS Concepts. QoS represent the users' point of view of the system performance, and GoS, the network's point of view. These are specified in the ITU-T Recommendations E.800 and E.600 respectively [15]. With respect to QoS, in addition to call blocking (when all channels in a cell are occupied), a call can be dropped, due to either the ever changing channel fading characteristics, or when being handed over to an already full adjacent cell. With data streams, parameters such as throughput, packet loss, delay and jitter, typical of Internet networks, are now also important. Specifically, real – time traffic and streaming traffic are more sensitive to packet level delay and to end – to – end delay, respectively. QoS is in turn provisioned by employing bearer services. These are the predetermined performance provisioning packages that the network promises to offer for a specified type of user traffic. Fig. 4 illustrates this evolution of QoS provisioning architecture, comparing bearer service architectures from 3GPP Release '97/98, Release 5, general UMTS and that of the Evolved Packet Core.



QoS architecture in Rel'97/98

QoS architecture in Rel'5

UMTS QoS architecture

LTE QoS architecture

Fig. 4: The Evolution of Bearer Services in Mobile Cellular Networks

Tools and Methods. With MCNs, drive testing has been the go to method of traffic and system performance measurement from the beginning. The proliferation of data services has made traffic trace collection and analysis important as well. Drive testing gives a very realistic but narrow view of user perceived network performance since it only serves users in the sites visited. More comprehensive measurements are available with the network service provider. Usually this data is very sensitive and hence not very readily available for use in, for example, academic research. Similarly, network monitoring is usually done by either the service providers or the regulatory authorities. There is an opportunity of collaboration between academic institutions and the data collection entities for improved service engineering.

Erlang introduced mathematical analysis in network optimization. Here it was possible, knowing any two parameters of the performance triangle, to predict the third parameter. Assuming the arrivals to be Poisson and infinite, mathematically tractable analytical models have been developed. The choice of the analytical model would depend on whether rejected calls are blocked out indefinitely, allowed to retry the call or wait in a queue. Table 2 outlines these models and the assumptions that were made. It should be noted that computer simulations have also been employed in TE analysis.

Table 2. Teletraffic Engineering Analytical Models. (Sources: [1 - 4])

Model	**Performance Formula**		**Assumptions**	**Limitations**
	Loss System	**Waiting System**		
Poisson	$P=1-e^{-A}\sum_{i=0}^{N-1}(\frac{A^i}{i!})$	NA	If blocked, calls wait for the entire service duration	In cellular networks users attempt calling multiple times after rejection
ErlangB	$P_j=\frac{\frac{a^j}{j!}}{\sum_{k=0}^{s}\frac{a^k}{k!}}$	$P(s,a)=\sum_{j=s}^{\infty}\frac{a^j}{j!}e^{-a}$	Infinite number of sources create a Poisson stream; Service time is exponentially distributed	In cellular systems there is only a few callers per cell hence sources not infininte
Engset	$P(b)=\frac{[\frac{(S-1)!}{N!(S-1-}}{(\sum_{X=1}^{N}[\frac{(S-1}{X!(S-1}}$	$C(s,a)=\frac{\frac{a^s}{s!(1-}}{\sum_{k=0}^{s-1}(\frac{a^k}{k!}+\frac{}{s!}}$	There is a finite number of sources	Cellular calls still assumed to bea Poisson process, contrary to reality
Pascal (Palm - Wallström)	(Same as Engset)	NA	Arrivals more bursty than random traffic (Pareto inter-arrivals)	A complex, multi-parameter model

Related Work. Surveys on the teletraffic aspects of MCNs began with the 2G revolution of these networks. Jabbari [19] gave an extensive cross sectional review of works in all aspects of the network functionality. It was noted that with circuit switched voice only traffic, traditional Erlang models for traffic intensity and arrival, as well as estimates for blocking probabilities could be used. Slight modifications would be made to the traffic intensity and the traffic process to include handoff traffic, overflow traffic, database traffic and control traffic, where applicable. Also performance parameters would increase to also include those that are either influenced by user mobility, position within the cell, as well as the variations in the wireless channel characteristics. New QoS measures emerged with the addition of different network functionalities. Moreover, Poisson traffic sources evolved into multi-state Markov modeled sources to signify either heterogeneous traffic, multi-tiered cell structures, or multi-priority traffic classes. Mathematical analysis was however dominant in the period, with computer simulations used to implement algorithmic solutions in a few instances.

Wirth [36] noted that the evolution of MCNs across the generations has brought about the merging of telephony with computing, and an equal acceleration in the device manufacturing industries. The resulting new challenges in the engineering of mobile cellular networks have completely disrupted traffic engineering practices. She urges for a new look into the fundamental traffic models as well as the subsequent provisioning mechanisms.

Basharin [38], surveyed the modeling of unicast, multicast and elastic network links serving video, telephone and data signals. Here it was noted that the links were usually modeled as queuing systems, including First Come First Serve queues (unicast), Transparent Queues (multicast) the Processor Sharing Queue model (elastic). It was further noted that the extended multiservice Erlang model could be used to analyze the performance of the unicast queues whereas multicast queues employed the numerical Kaufman – Roberts method for numerical solution of performance equations. These studies failed to outline the relationship between advances in network technologies and TE practices.

2.3 State of the Art

Currently, MCNs are at the point of standardizing the fifth generation. One prominent traffic engineering paradigm that has kept evolving since the 3G era has been Cross Layer Optimization. To optimize resources, the physical layer characteristics have been noted to affect the upper layers. Moreover, since TCP traffic is now significant in mobile cellular networks, its dynamics affect the traffic profile of the network. As a result, solutions now advocate for channel aware scheduling, application aware traffic classification, as well as TCP implementations that are aware of both the channel conditions and the MAC layer flow controls. Furthermore, the current multiple service networks adhere to SLAs through service differentiation like in the Internet. The shift nowadays is towards dynamic bearer set up, where, for example, a user may be provisioned according the their most demanding application, and when relatively inactive but still online, dynamically assign this user's resources to other users.

Also, as noted previously, traffic engineering is moving away from mathematical analysis, towards simulation. Traffic engineering is an optimization problem, the more the parameters, the more complex the optimization problem and the more difficult it is to solve the problem analytically; hence algorithms are designed, that guarantee the network reaching an optimum operating point while in operation.

3 Methodology

This survey relied heavily on qualitative document analysis. Through purposive sampling, Google Scholar was chosen as the source database for surveyed works since it is believed to contain almost 88% of all published works [39]. A comparison with a search in Microsoft Academic showed only 3 articles missing from Google Scholar among the top 20 most relevant articles. The units of data analysis included theses and dissertations, journal articles, conference papers as well as book chapters. The units of data analysis were sampled according to a non-probability convenience sampling method where all 38 relevant academic resources that responded to the search key-phrases including a combination of words "teletraffic, traffic, engineering, mobile, cellular, networks" were reviewed. This sampling method alienated potentially relevant data analysis units presented in languages other than English. Moreover, patent documents were not included in the analysis. The performance triangle as a basis for traffic engineering was leveraged into designing the categorization of the data units and a subsequent framework for their assessment as illustrated in Table 3. The analysis of the data units involved simple statistical calculation of relative frequencies and observations by comparison on the checklist in Table 3. To obtain trends, the analysis was done by arranging the analyzed works in a chronological order.

Table 3. Teletraffic Engineering Studies in Mobile Cellular Networks.

Author & Year	Mobile Cellular Network Technology	Traffic Characterization	Performance Triangle Parameter	Tools and Methods Used

4 Results

The analysis revealed that there was very litle (2.5%) work done in mathematical analysis of MCNs in 1980s with 1G analog MCNs. The studies peaked at 40% of the reviewed works in the 1990s. The numbers fell again in 2000s to 20%. Starting from 2010, the reviewed documents make 37.5%. In 1990s the analysis was on the performance of abstract models of MCNs and sometimes confining the analysis within a particular multiple access technology. In the 2000s, the technological focus of the analysis was in the revoluitonary data-servicing 3G networks whereas starting from 2010, there is an observable moving focus from 3G, to 4G and beyond as years progress. As noted in Table 4, in the 1990s, teletraffic engineering was heavily based on modeling MCNs starting from the legacy Erlang models. In the 2000s, the developed models were mostly used in performance evaluation of the network services. More recently, literature surveyed shows a trend towards using teletraffic engineering for service scenario definition. It is clear from Table 4 that as the network technologies evolved to provide higher speeds and capacities, the engineering challenge shifted from simple dimensioning to service optimization. An evolution in the analysis methods from single mathematical models, to a combination of models, to simulation can also be noted.

Table 4. Teletraffic Engineering Studies in Mobile Cellular Networks.

Year	Technology	Traffic Characteristics	Objective	Tools and Methods	Notes
1992 – 2000 [16 -28]	FDMA, CDMA, TDMA as well as generalized mobile cellular network	Predominantly voice calls; fresh, handed over, overflown The spatial aspect of mobile traffic also features in many of these studies	Early 90s - extending Erlang models in network performance evaluation. Mid 90s - traffic characterization as well. End of the 90s- comparison, among analytical tools, simulation and measurements. Some attempts to model service time distributions, contrary to the assumption of the exponential distribution	Erlang models, extended Erlang models, Simulation ; with tools e.g. ICEPT tool	Employing macrocells over microcells as a solution to the capacity problem Also demand based network planning proposed
2001 - 2009 [29, 30]	3G networks	Both studies featured multimedia traffic mixtures	User perceived network performance	Erlang loss formula, the Processor Sharing model in the Ocelot network planning and optimization tool	Both studies were assessing the performance of 3G technologies
2011 – 2017 [31 - 35]	Generalized cellular networks, and specifically, 3G, 4G and beyond	General traffic , with emphasis on traffic mixture characterization	Performance analysis with novel models of traffic processes and models of network technology advances	Traditional models; other mathematical tools and methods	Mostly modeling and performance analysis of the new QoS mechanisms

5 Discussion

5.1 Trends

Trends in the Evolution of MCNs. The evolution of MCNs has happened in multiple aspects as a result of the ever evolving service demand scenario. Data transmission capabilities have evolved across years from being able to support only textual data to a point where high definition multimedia interactivity is now supported. Reviewed works show this trend in the ever changing traffic models that have evolved from simple Poisson processes to Interrupted Poisson Proccesses or multi-state Markov Modulated Poisson Processes. Moreover, traffic mixtures are now predominant in TE of MCNs. The introduction of sectorization has reduced interference but also reducing capacity hence introducing another performance trade-off in MCNs. Similarly, the evolution from macro-cells to micro-cells to pico- and femto-cells has dictated the change in the propagation environment which together with secotrization has dictated TE models with overflow traffic and increased proportion of handovers as evidenced in studies in 2010s. Transport methods have become more spectral efficient but interference limited. Consequently QoS functions have shifted from reservation centric to opportunistic service differentiation centric methods. The move from technolgy driven to user driven to service driven evolution of MCNs is evidennt in the fact that earlier studies mostly extended Erlang models to fit MCNs; in the mid 2000s, these models were used extensively to analyze performance of existing systems for use satisfaction. Studies in 2010s, show a trend towards applying TE as a tools to design new service scenarios as well as QoS management schemes.

Trends in the Evolution of TE of MCNs. TE was predicted to drastically change as the variables in the TE optimization problems increased [12]. Back then, however, most of the research concentrated on the modeling of the traffic demand, taking into account the influence that the spatial and temporal changes of user locations had on the distribution of traffic offered to the network. With GoS, emphasis has shifted from only network resources availability to also include the resource reliability as evidenced by the performance centric studies in the 2000s.

Moreover, the incorporation of data services over mobile networks saw the increased importance of admission control and scheduling mechanisms for assurance of adherence to SLAs. Internet centric TE was therefore adopted while leveraging the challenges posed by the air interface rather than mitigating them. Examining the studied documents shows traffic management mechanisms that are not only focused on thtroughput but also fairness in user service.

Furthermore, more realistic traffic arrival and service time models proved to be mathematically intractable. This gave rise to the use of computer simulations as an important traffic engineering tool. The most notable change in traffic models is the inclusion of handover, and in hierarchical designs of overflow traffic.

There have been interesting developments in the the mathematical methods employed in Operations Research. Although only a few studies have attempted this route, there is a noted trend in employing such tools as genetic algorithms, fuzzy logic, neural networks, heuristics, control theory, and game theory into developing more accurate and more parsimonious models, as well as realistic simulations and emulations of traffic engineering problems.

The Relationship Between TE and the Evolution of MCNs. The two concepts show cycles of one influencing the other in turns. Fig. 5 is a summary of this complex relationship where advances in each field influence the maturity of the other field.

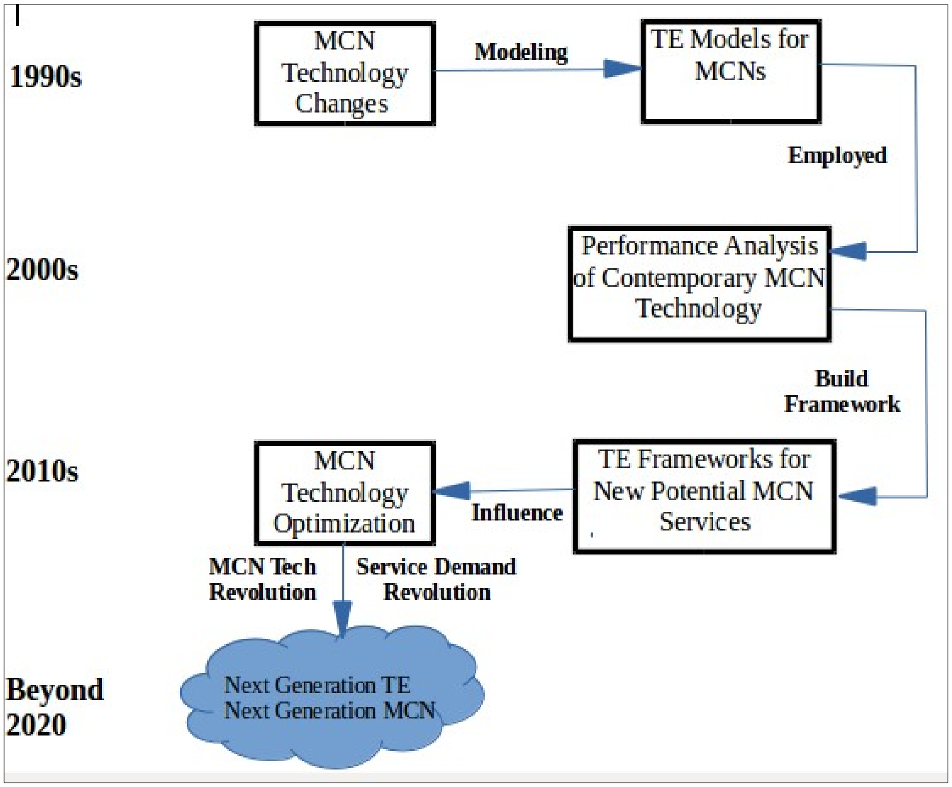


Fig. 5: The Relationship between MCN Evolution and Changes in TE Paradigms

5.2 Opportunities

So far, most authors have used mere modifications of prior traffic models in their studies. With the seminal work by Leland and Taqqu that highlighted the multifractal nature of packet traffic, researchers began venturing into fitting common long tailed distributions into empirical packet data. Overall traffic profile would hence be a combination of different traffic classes. Currently, enough data has been gathered over several implementations of mobile cellular networks to allow for the derivation of parsimonious traffic models. There is even a chance for TE to dictate how next generation applications should behave to fit the next generation networks for the desired performance.

With the current move towards the Internet of things (IoT), it is expected that traffic characteristics will be very much influenced by the service profile rather than the user profile. Information about the network is available wherever the device may be. This drive should as a consequence render traffic measurements and monitoring much easier by employing crowd-sourcing. There is therefore a big challenge and hence an opportunity to engineer mobile cellular networks that make it easy to share user perceived network conditions without compromising the users' privacy and security.

6 Conclusion and Recommendations

This study was set out to investigate the complex relationship between the paradigm shifts in TE with respect to the evolution of MCNs across their now five generations. At the inception of cellular networks, TE was a simple extension of the then well established Erlang analytical models. The subsequent revolution of cellular networks saw traffic engineering failing to catch up with the design challenges posed by the ever changing service scene in MCNs. However, we are now at a point where advances in both technology, mathematical tools and communications have helped to ease knowledge dissemination and quickly fill the gaps between disciplines. There is now an opportunity, for a revolution in TE tools and methods that could be developed and standardized to optimize the current MCNs as well as predict the next usage scenarios.

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