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From LTE to 5G for Connected Mobility

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The authors measure how current LTE network implementations perform in comparison with the initial LTE requirements. The target is to identify certain key performance indicators that have suboptimal implementations, and therefore lend themselves to careful consideration when designing and standardizing next generation wireless technology. Specifically, they analyze user and control plane latency, handover execution time, and coverage, which are critical parameters for connected mobility use cases such as road vehicle safety and efficiency.

Abstract

Long Term Evolution, the fourth generation of mobile communication technology, has been commercially deployed for about five years. Even though it is continuously updated through new releases, and with LTE Advanced Pro Release 13 being the latest one, the development of the fifth generation has been initiated. In this article, we measure how current LTE network implementations perform in comparison with the initial LTE requirements. The target is to identify certain key performance indicators that have suboptimal implementations and therefore lend themselves to careful consideration when designing and standardizing next generation wireless technology. Specifically, we analyze user and control plane latency, handover execution time, and coverage, which are critical parameters for connected mobility use cases such as road vehicle safety and efficiency. We study the latency, handover execution time, and coverage of four operational LTE networks based on 19,000 km of drive tests covering a mixture of rural, suburban, and urban environments. The measurements have been collected using commercial radio network scanners and measurement smartphones. Even though LTE has low air interface delays, the measurements reveal that core network delays compromise the overall round-trip time design requirement. LTE's break-before-make handover implementation causes a data interruption at each handover of 40 ms at the median level. While this is in compliance with the LTE requirements, and lower values are certainly possible, it is also clear that break-before-make will not be sufficient for connected mobility use cases such as road vehicle safety. Furthermore, the measurements reveal that LTE can provide coverage for 99 percent of the outdoor and road users, but the LTE-M or NarrowBand-IoT upgrades, as of LTE Release 13, are required in combination with other measures to allow for additional penetration losses, such as those experienced in underground parking lots. Based on the observed discrepancies between measured and standardized LTE performance, in terms of latency, handover execution time, and coverage, we conclude the article with a discussion of techniques that need careful consideration for connected mobility in fifth generation mobile communication technology.

Introduction

The third and fourth generations (3G and 4G) of mobile communication technologies are widely deployed, providing voice and mobile broadband as their main services. However, due to the increasing demand for higher data rates and larger system capacity [1], in addition to the emergence of new Internet of Things use cases, the fifth generation (5G) is currently being discussed. 5G is expected to be standardized and deployed in 2018 and 2020, respectively. A key scenario for 5G is connected mobility, which utilizes vehicular communication for such things as infotainment, safety, and efficiency [2]. The two latter uses impose new and challenging requirements in terms of low latency, zero handover interruption time, and ultra-high radio signal reliability [3].

While these requirements are already in the scope of 5G standardization, the ability to meet the requirements in practice is more important than ever in view of the criticality of the safety-oriented connected mobility use cases. These cases rely on vehicular communication for such capabilities as platooning, cooperative awareness, and self-driving cars [2]. In this sense, there is learning to be had from network testing on the already established 4G Long Term Evolution (LTE) infrastructure, to see if the original LTE requirements are met in practice, and if not, evaluate whether the current 5G developments are likely to minimize the gap between requirements and commercial implementation. In this article, we look at the initial design requirements of 4G LTE and the observed performance in terms of user and control plane latency and LTE handover execution time. In view of this, we discuss how 5G may be designed to address the latency and handover requirements of connected mobility use cases such as vehicular communication for safety and efficiency. Our analysis is based on an extensive measurement campaign of LTE performance in four cellular networks in Northern Jutland, Denmark. The campaign included 19,000 km of drive test with commercial radio network scanners and specialized measurement smartphones. Furthermore, we use the measurements to calibrate a radio wave propagation tool to study radio coverage, because it is a prerequisite for good latency and handover performance.

The LTE latency and handover performance has previously been studied, for example, in [4–7]. However, the scope of our measurement campaign in terms of number of studied operators, network configurations and topologies, device speeds, and scenario areas is unprecedented to the best of our knowledge. Specifically, we study four commercial operators covering both rural, urban, and suburban areas, totaling 19,000

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km of drive test at speeds from 30 to 130 km/h using specialized measurement smartphones, which provide information on not only application layer performance but also radio resource control (RRC) messages. This is a significant statistical improvement compared to [4], which is based on three days of measurements in a single, lightly loaded, urban network with line-of-sight connection, and [5], which is based on 35 km of urban drive test, and [6], which is based on field trials, where the core network (CN) was located close to the trial area to reduce the latency. The report [7] relies on data collected in the Nordic countries from 22,000 users via a smartphone application in January through March 2016, but it only provides information on data rates and user plane latency. Therefore, the statistical representation of our measurement data and the availability of network parameters ensures a solid comparison with the design requirements, enabling us to identify any discrepancies.

The article is structured as follows. First, we describe the extensive measurement campaign. Then the latency and handover performance observations are presented. Next, we present the LTE coverage and discuss how it can be extended. Then we identify discrepancies and areas for improvement by comparing the LTE requirements with the observed performance, and discuss how the 5G development can address these issues.

Measurement Campaign

The extensive measurement campaign was conducted in the region of Northern Jutland in Denmark. The region has about 585,000 inhabitants over an area of 8000 km^2. A large part of the region is rural area with small villages and farmland, and only few larger cities with population size in the 10–20,000 range and one major city of 130,000 inhabitants. The wireless infrastructure in the region is well developed. As was revealed in the measurement campaign, at least one operator provides all technologies over the full region. If two operators are required for 3G/4G coverage, about 60 small areas (of 0.5–4 km radius) experience limited or no coverage.

The drive test measurements were made using two cars covering about 19,000 km of city roads, rural roads, and highways within the region, and therefore includes measurements in the range of 30–130 km/h. During the drive test, samples of received signal power, data rate, round-trip time (RTT), and radio access network (RAN) specific parameters were collected simultaneously for the four main operators in Denmark. The road coverage, based on more than half a million collected data points, is illustrated in Fig. 1. The measurements were made during the daytime Monday through Friday in the period from November 2015 to May 2016. Note that the status of the four networks may have changed during the long measurement campaign, in terms of both deployed base stations and equipment, but also in terms of number of users and network load. However, this information is not publicly available; therefore, the measurement campaign reflects the performance at the specific time of measurement.

Each car, moving according to local traffic rules, was equipped with a roof box containing a Rohde & Schwarz FreeRider III system. The system consists of four Samsung Galaxy S5 Plus smartphones, running specialized QualiPoc measurement software, and a TSME radio network scanner. The smartphones reflect the user experienced performance and, in addition, are able to record relevant network parameters such as RRC messages. Each phone was connected to one of the four main mobile network operators of Denmark using either 3G or 4G depending on the current signal levels and operator traffic steering policies, while the scanner passively monitored the allocated frequency bands for 2G, 3G, and 4G communication from 700 MHz to 2.7 GHz. We only report results for 4G in this work. The smartphones and the scanner measured the received signal power from the serving cell and all observable neighbor cells, respectively. The scanner was equipped with an external, omnidirectional Laird TRA6927M3NB-001 antenna, which was mounted in the roof box on a separate ground plane. In addition, the position was logged per measurement sample via GPS and used to generate averages of the received signal power over 50 m road segments.

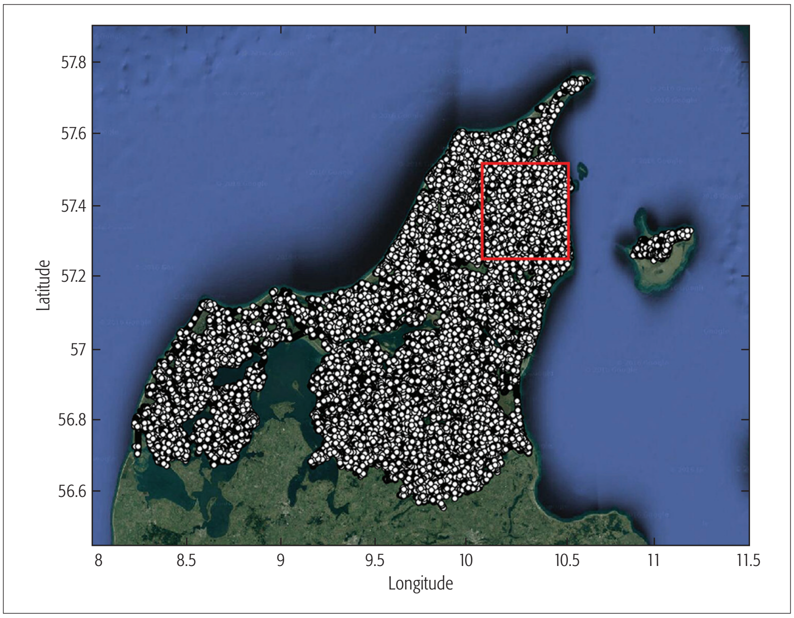

Figure 1. Overview of measurement locations in Northern Jutland. The red rectangle indicates the area that is examined in the coverage study.

Each smartphone continuously performed a series of data measurements consisting of four fixed duration FTP transfers in uplink and downlink (alternating link directions, i.e., eight transfers in total), each 20 s long, to estimate the broadband coverage. The FTP transfers were followed by a 10 s idle period and preceded by two ping measurements occurring with 1 s separation. The ping and FTP measurements were made toward a server located at Aalborg University (AAU). The server was connected via 10 Gb/s fiber to the Danish Research Network, which is connected to the Danish Internet Exchange Point via another 10 Gb/s fiber, and thus the link between the Internet and the server is expected to have minimal impact on the measurements. Ping measurements made from a computer located at AAU toward the server, passing through the Danish Research Network, result in average RTTs of 7.5 ms with a standard

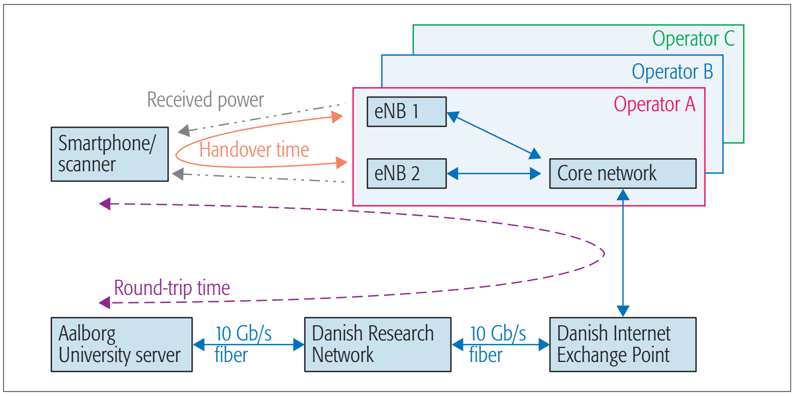

Figure 2. The measurement configuration including network connectivity and KPIs.

deviation of 0.6 ms. Figure 2 emphasizes the key performance indicators (KPIs) considered in this article — RTT, handover execution time, and received signal power — and how the KPIs relate to the network configuration in the measurement campaign. Notice that each of the operators have a direct link to the Danish Internet Exchange Point. Furthermore, two of the operators share their networks, and therefore their measurement results are combined in this work.

Latency Performance

Latency or RTT performance is a KPI for user quality of experience. The emergence of the connected mobility use cases for safety makes it even more critical to deliver data and responses with low latency [2]. Latency can be divided into control plane latency, which is the time it takes the device to transfer from the RRC Idle state to the RRC Connected state and be able to transfer data; and user plane latency, which is equal to the RTT of a data packet and its associated acknowledgment from the target layer, assuming the device is connected with the network. In LTE the control plane latency target is 100 ms, while the user plane latency target is 20 ms [8].

Figure 3 shows the cumulative distribution function (CDF) of the two ping measurements performed using LTE. The second ping, performed 1 s after the first ping, is a good measure of the user plane latency, because the 1 s delay allows sufficient time for entering an RRC Connected and schedulable state. According to [6] the RTT of LTE, excluding the CN delay, is approximately 19 ms when the user equipment (UE) does not have pre-allocated resources, and therefore a scheduling request in uplink is triggered. During high network load and/or poor radio signal conditions, this value will increase due to scheduling delays, low data rates, and retransmissions. As mentioned previously, the AAU server to Danish Research Network RTT, illustrated in Fig. 2, was measured to be 7.5 ms, and furthermore the RTT between the Danish Research Network and the Danish Internet Exchange Point is estimated to be 1 ms. The total latency, excluding the CN, is thus about 27.5 ms, which fits with the observation of Fig. 3a where the lowest observed RTT is 28 ms. Scheduling delays, low data rates due to network load and insufficient coverage, and retransmissions contribute to the 95th percentile being 67, 160, and 120 ms for operators A, B, and C, respectively. However, even the best 5th percentile experience latencies 7.5, 33.5, and 21.5 ms above the expected 27.5 ms for operators A, B, and C, respectively. Clearly, the CN latency, which is the time it takes the packet to transfer from the S1 interface between eNB and the serving gateway through the operator's backhaul to the Danish Internet Exchange Point, is a major limitation, especially for operator B, whose best 5th percentile users experience latencies more than 100 percent higher than the expected 27.5 ms. The observed delays are significantly longer than [4], which noted an average LTE user plane latency of 36 ms and CN latency of 1–3 ms. However, those measurements were made in a network with a limited number of users and from a static, line-of-sight measurement position. The average user plane latency was noted to be 45 ms in [7], but it is not clear how the users were distributed geographically (and whether they were indoors or outdoors) as the coverage was claimed to be less than 80 percent even for the best operator. This is in contrast with our finding of approximately 99 percent outdoor LTE coverage, which is described later.

In general, operator A provides the lowest user plane latencies; this is correlated with the fact that operator A provides the best LTE coverage in the area. The standard deviation of the latency of operator B is 69 ms, significantly larger than those of operators A and C, which are 22 and 33 ms, respectively. The reasons for the latency jitter may include varying load across the network and thus varying scheduling delays and data rates, but also less consistent routing of packets in the CN. Independent of the reason, it is an issue for safety-critical connected mobility, which requires predictable and steady latency performance.

The first ping, which is performed after 10 s of idle time and illustrated in Fig. 3b, is a measure of the control plane latency combined with the user plane latency of Fig. 3a. Since the server is addressed via IP, there is no additional delay incurred due to Domain Name System lookup.

The inactivity timer of LTE, that is, the time between the last data transfer and until the network moves the UE to RRC Idle, is on the order of 5–10 s for most networks, which explains why some UEs in the CDF of ping 1 in Fig. 3b experience performance similar to ping 2. Excluding the UEs that seem to be RRC connected when ping 1 is initiated, and subtracting the average RTT observed in Fig. 3a, the lowest control plane latency is on the order of 120 ms for operators A and B and 80 ms for operator C. Some users experience longer latencies, which may be due to a failed random access (RA) procedure in addition to the aforementioned RAN contributors. Independent of the operator, there are some distinctive steps that occur at intervals of 40 and 80 ms. This corresponds well with the periodicities of system information blocks 1 and 2, which are needed by the UE to perform cell access and RA [9]. Similar to the user plane latency result in Fig. 3a, operator A performs best in Fig. 3b, but when the user plane latency is subtracted from the measurements, the three operators perform very similarly.

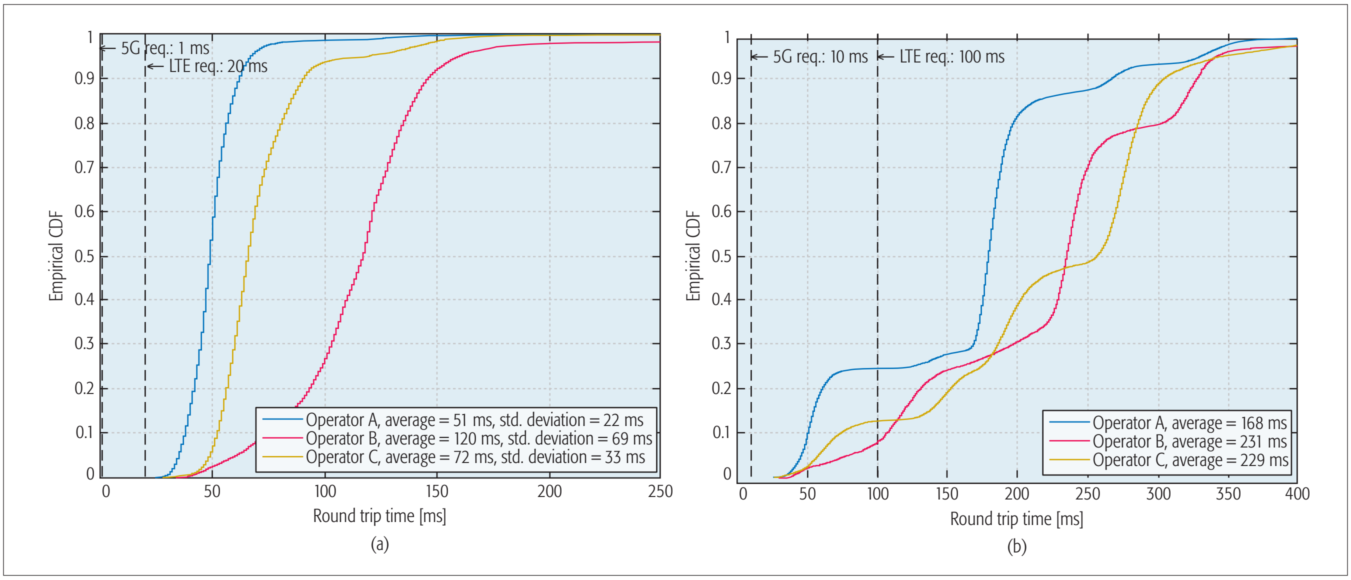

Figure 3. The LTE ping measurement results. Note the AAU server RTT is 7.5 ms, which must be added to the LTE requirement line for result interpretation: a) CDF of ping 2 — user plane latency; b) CDF of ping 1 — control plane latency.

Handover Execution Performance

LTE implements break-before-make handover, where the UE breaks data exchange with the serving cell before establishing a connection toward the target cell. As a result, the UE experiences a service interruption at each handover for a short period of time. Upon reception of the handover command or the RRC Connection Reconfiguration message, which includes the mobility control information [9], the UE proceeds to reconfigure layers 2 and 3, terminating any data exchange with the network. Afterward, it performs radio frequency retuning and attempts RA toward the target cell. When completed, the UE sends the RRC Connection Reconfiguration Complete message to confirm the handover, informing the target cell that the data flow can be restored. The stage that encloses the procedures between both RRC messages is called handover execution [6]. In order to detect problems during handover execution, the UE initiates timer T_{304} after receiving the handover command. If the MAC layer successfully completes the RA procedure, the UE stops the timer. However, if timer T_{304} expires before the handover has been completed, a handover failure is declared, and the UE shall perform connection re-establishment [9].

Ideally, the time it takes to perform the handover execution is a lower-bound of the handover service interruption time. In practice, there are additional delays such as UE and eNB processing times and propagation delays that may increase the overall service interruption. Current Third Generation Partnership Project (3GPP) studies on LTE latency report a typical handover execution time of 49.5 ms [10], while the International Telecommunication Union (ITU) target is 30–60 ms [8].

The QualiPoc measurement smartphones collect the RRC signaling exchanged with the network. Therefore, the handover execution time is determined by analyzing the timestamp of the RRC messages at each handover. Figure 4 depicts the CDF of the handover execution times measured on each of the analyzed networks. The number of registered handovers differ between networks: 161,313, 46,517, and 148,011 handovers for operator A, B, and C, respectively. However, the measured handover execution times are similar across them. As illustrated in Fig. 4, the extracted times are below 75 ms in 90 percent of the cases with a median value of approximately 40 ms, which is in line with the expected typical value of 49.5 ms reported by the 3GPP [10] and the 30–60 ms target of ITU [8]. The average handover execution time is reported to be 30 ms in [5], but the measurement only covers 35 km of urban drive test. Similarly, [6] reports average times around 25 ms, but for a field trial where the CN was located close to the trial area.

Figure 4 also illustrates handover execution times larger than 200 ms, and some are due to unsuccessful handovers (approximately 1 percent of the total number of samples). In these cases, a handover failure is declared, and the connection re-establishment increases the data interruption time up to several seconds. These extreme values show that the LTE handover execution with a break-before-make implementation may become an issue for the safety-critical connected mobility use cases with stringent latency requirements.

Coverage Performance

The requested latency and handover performance cannot be achieved without sufficient radio coverage. As mentioned earlier, the 4G coverage is good in the region, but since the measurements are performed as drive tests, they only indicate road coverage. However, the connected mobility use cases focused on vehicular communication for safety and efficiency also require indoor coverage, for example, for underground parking lots and integral garages. Therefore, the extensive measurement campaign was used for calibration of a radio wave propagation tool in order to estimate the received signal power for a selected rural area of the region. The area under study is approximately 800 km^2 and is based on a local operator's commercial deployment of 71 eNB sectors operating in LTE band 20 ($\sim$ 800 MHz).

The area is illustrated with a red rectangle in Fig. 1. An elevation map, obtained from Kortforsyningen [11], is imported to account for terrain variations and combined with a log-normal shadow fading of 8.7 dB variance, which was estimated using the received power values from the measurement campaign. The area is divided into 50 × 50 m pixels, and the coupling loss is then determined between each pixel and the 71 eNB sectors. The coverage is evaluated for different user groups, which are assigned to specific pixels based on public database information. The first set is outdoor users, located in pixels that contain a house number based on Open Street Map, and road users, located in pixels that contain a road segment [11]. The other group consists of indoor users, which are also identified by house numbers. The indoor users are divided into 3 subgroups, experiencing 10, 20, and 30 dB penetration loss in addition to the observed coupling loss. The indoor groups are generated to study a light indoor scenario, where, for example, a user is located close to a window and thus only experiences 10 dB additional loss, and deep indoor scenarios, where, for example, a user is located in a basement such as an underground parking lot and therefore suffers 20–30 dB additional loss [12]. For further details on the simulation setup refer to [11].

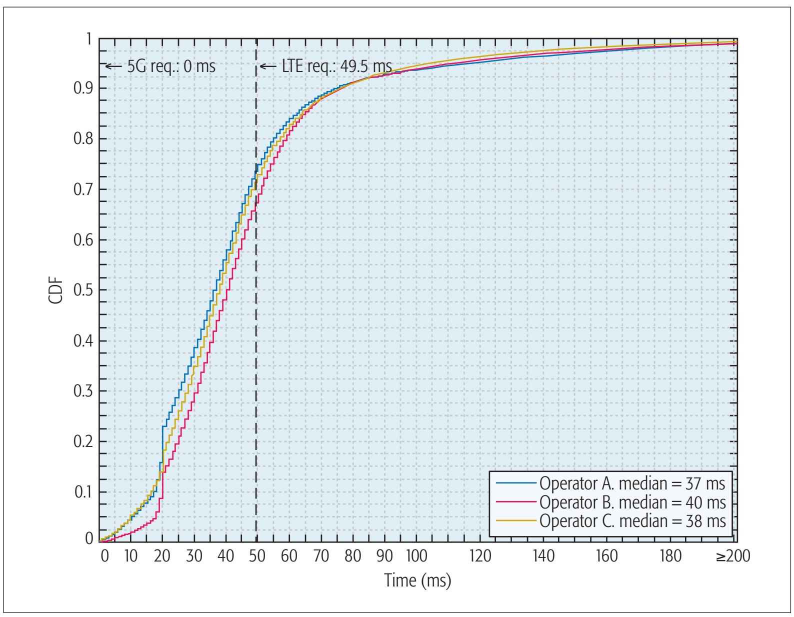

Figure 4. CDF of the handover execution time measured during the drive tests for each operator.

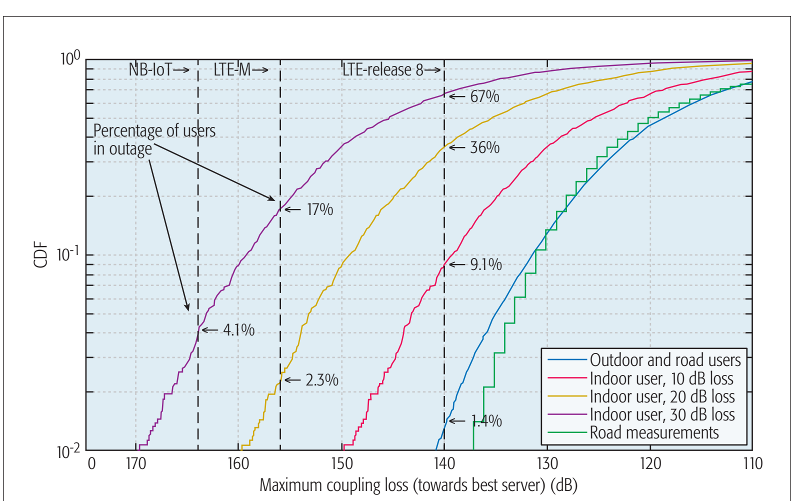

Figure 5. Coverage performance for LTE, LTE-M, and NB-IoT. Based on Fig. 3 of [11].

Figure 5 shows the coupling loss between the UE and the serving cell, which is selected based on the strongest received signal. The three dashed vertical lines indicate the supported maximum coupling loss (MCL) for LTE Release 8 (140 dB), LTE-M Release 13 (156 dB), and Narrowband Internet of Things (NB-IoT) Release 13 (164 dB) [13]. The two latter technologies achieve higher MCL by applying repetitions in time (at the cost of latency!) and power spectral density boosting in smaller transmission bandwidths of 1.4 MHz for LTE-M and 200 kHz for NB-IoT. Note that NB-IoT does not apply handovers, but only cell reselection. Figure 5 also contains road measurements obtained in the area indicated by the red rectangle in Fig. 1. The curve shows a good fit with the simulation of outdoor and road users, and the minor difference is attributed to remote houses in the area that are located far from the road measurements.

The results in Fig. 5 indicate that LTE Release 8 provides sufficient coverage for 99 percent of the outdoor and road users. If indoor coverage is needed LTE Release 8 provides coverage for only approximately 90 percent of light indoor users, experiencing 10 dB additional penetration loss. For deep indoor users, NB-IoT is required and can provide coverage for about 95 percent of the users. However, for most of the safety and efficiency use cases, outdoor and road users can rely on LTE Release 8, and thus also benefit from the larger bandwidth and lower latency of this technology.

Enabling Connected Mobility in 5G

The connected mobility use cases, focused on road vehicle safety and efficiency, demand low latency, high reliability, and zero handover execution time [2, 3]. These parameters were also defined for LTE, but using different values since mobile broadband and voice applications were mainly targeted. In Table 1 the LTE requirements are compared to the results of the extensive measurement campaign, which represents what is achievable in commercially deployed networks. In addition, the current 5G targets are listed together with highlights of ongoing 5G research on how the mobile communication system can improve compared to LTE and address the discrepancies between standardized and measured performance. These comparisons are important in order not to experience similar performance discrepancies when 5G is deployed.

The measured LTE user plane latency (Fig. 3a) is significantly higher than the 20 ms target [8] for all operators. However, the key observation is that there is an even larger difference (51 vs. 121 ms) between two operators. Since the air interface is the same and assumed to have comparable loads, it is clear that RAN setup, routing, and CN architecture have a major impact on user

Parameter	LTE requirement	Measured LTE performance	5G target	Potential techniques
User plane latency (RTT)	20 ms	Average: A: 51 ms, B: 121 ms, C: 72 ms. Even the users in the best radio signal conditions are affected by long core network latency.	1 ms	Semi-persistent scheduling and combining of requests and data, processing time reduction, shorter TTIs, mobile edge computing, network slicing
Control plane latency (idle-to-active time)	100 ms	A and B require 120 ms, while C completes in 80 ms. Subsequent access attempts are delayed by long system information block periods.	10 ms	Optimized random access and security setup, periodicity of system information blocks, network slicing, and mobile edge computing
Handover execution time	49.5 ms	Similar median LTE values for all the operators of ~40 ms	0 ms	Make-before-break, multi-cell connectivity, UE autonomous cell management, synchronized handover
Supported maximum coupling loss	140 dB	LTE Release 8 provides coverage for 99 percent of the outdoor and road users in the rural area under study.	164 dB	Micro and macro diversity, TTI bundling, cell densification, power spectral density boosting

Table 1. Comparison of requirements, measured performance, and potential techniques for improvement.

plane latency. When designing 5G, it is therefore important to minimize the probability and impact of poor RAN and CN implementations on the envisioned new and optimized air interface. In addition, 5G research is targeting reduction of the user plane latency to 1 ms, [3] by use of shorter transmit time intervals (TTIs), bundling of scheduling request and data, decreased processing times obtained due to technology improvements, and potentially semi-persistent scheduling. Fortunately, work is also ongoing to optimize the RAN and CN. For example, the use of mobile edge computing, where processing and decision making are moved toward the eNB, is studied. Moreover, the 5G network is expected to rely on flexible slicing of the RAN and CN, and splitting of tasks between edge and central clouds to accommodate the requirements of the different use cases [14].

The control plane latency of LTE was targeted to be 100 ms or less [8], and one operator fulfills this, achieving 80 ms on average, while the two other operators require approximately 120 ms, as illustrated in Fig. 3b. However, subsequent access attempts are delayed significantly due to the 80 ms or higher periodicity of the system information blocks, which provide the information the UE needs in order to access the network. The 5G target is 10 ms, [3], and therefore the required access information must occur more frequently, at the cost of increased control overhead. Additionally, work is ongoing to develop new RA and registration methods to enable the UE to connect faster and with more consistent performance. The control plane latency will also benefit from the use of network slicing, for example, by applying faster RA schemes to time-critical applications, and using different control channel modulation and coding schemes for different applications as well as mobile edge computing, for example, by letting the eNB handle some of the tasks currently performed by the mobility management entity in LTE.

The LTE handover execution time target is 49.5 ms [10]. The measurement results in Fig. 4 show that the operators on average fulfill this target with a median of 40 ms. However, a radio link failure occurs in approximately 1 percent of the measurements, and the subsequent connection re-establishment procedure extends the handover execution time to several seconds. The connected mobility use cases targeting safety and efficiency require 5G to provide zero service interruption time; therefore, a significant amount of work is needed in this area [3]. One proposed solution is to apply make-before-break connectivity where the UE connects to the target cell before disconnecting from the serving cell. In 5G this may be expanded to multiple connections due to the expected use of multi-cell connectivity. The cost is increased UE complexity and simultaneous utilization of resources in multiple cells. This concept is similar to the Dual Connectivity Split Bearer Architecture of LTE, which potentially can be combined with UE autonomous cell management. The latter concept allows the UE to autonomously add and release different radio links, reducing the control signaling overhead. Finally, 5G may also utilize synchronized handover, which is a random access-less procedure where the synchronized UE and cells agree on when the handover shall occur.

The supported MCL of a mobile communication system defines the radio signal availability together with the network deployment and load. The LTE Release 8 MCL is 140 dB, and the calibrated simulation in Fig. 5 of a rural area showed that a commercially deployed network would provide coverage for approximately 99 percent of the outdoor and road users. However, the connected mobility use cases focused on safety must also work in deep indoor scenarios such as underground parking lots with higher coupling loss [12]. Therefore, a certain slice of 5G must support a higher MCL, potentially similar to the 164 dB of NB-IoT. Similar to NB-IoT the 5G design can thus rely on TTI bundling, that is, repetitions of transmissions in the time domain, which, however, will harm the latency, and use of power spectral density boosting, which may harm the signal-to-interference ratio of other users. Therefore, 5G will preferably utilize the expected network of ultra-dense small cells, macrocell densification, and micro and macro diversity to improve the received signal power and reliability [15].

The LTE handover execution time requirements and observed performance are similar, but since the connected mobility use cases targeting safety and efficiency require zero service interruption time, the 5G design must utilize new mobility methods such as make-before-break, multi-cell-connectivity and synchronized handovers.

Conclusion

In this study we examined the performance of four LTE operators in an extensive measurement campaign of 19,000 drive test kilometers. The goal was to identify gaps between LTE requirements and achievable performance in order to avoid similar discrepancies when 5G is standardized and deployed. The 5G will be able to support connected mobility use cases focused on vehicular communication for road safety and efficiency, but improvements are needed in the areas of user and control plane latency, handover execution time, and radio signal availability.

The LTE user plane latency is observed to be twice as long as the requirement due to core network latencies, and thus diminishes the effect of an optimized air interface. For 5G it will be of key importance that the operators focus on the latency of the core architecture in order to achieve the 1 ms RTT target. The studied networks roughly achieve the LTE control plane latency requirement, but since 5G requires it to be 10 times lower the amount of random access, connection and security setup signaling must be reduced. For both latency targets the use of mobile edge computing and network slicing will be beneficial.

The LTE handover execution time requirements and observed performance are similar, but since the connected mobility use cases targeting safety and efficiency require zero service interruption time, the 5G design must utilize new mobility methods such as make-before-break, multi-cell-connectivity, and synchronized handovers.

The simulated LTE outdoor and road coverage is sufficient for 99 percent of the users, but in order to ensure the connected mobility operation, it is suggested that 5G target a significant cell densification and use of macro and micro diversity to improve the radio signal availability.

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References

[1] Cisco, "Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015–2020," white paper, 2016.
[2] 5G Infrastructure Public Private Partnership, "5G Automotive Vision," white paper, 2015.
[3] 3GPP, "Study on Scenarios and Requirements for Next Generation Access Technologies," TR 38.913 V0.3.0, Mar. 2016.
[4] M. Laner *et al.*, "A Comparison Between One-Way Delays in Operating HSPA and LTE Networks," *Proc. 2012 10th Int'l. Symposium Modeling Optimization Mobile, Ad Hoc and Wireless Networks*, May 2012, pp. 286–92.
[5] A. Elnashar and M. A. El-Saidny, "Looking at LTE in Practice: A Performance Analysis of the LTE System Based on Field Test Results," *IEEE Vehicular Technology Mag*., vol. 8, no. 3, Sept. 2013, pp. 81–92.
[6] H. Holma and A. Toskala, *LTE for UMTS — Evolution to LTE-Advanced, 2nd ed.*, Wiley, 2011.
[7] Open Signal, "State of Mobile Networks: Nordics," May 2016, report; https://opensignal.com/reports/2016/05/nordic/state-of-the-mobile-network/, accessed Dec. 12, 2016.
[8] ITU-R M.2134, , "Requirements Related to Technical Performance for IMT-Advanced Radio Interface(s)," Nov. 2008.
[9] 3GPP, "Radio Resource Control Protocol Specifiation," TR 36.331 V13.1.0, Apr. 2016.
[10] 3GPP, "Study on Latency Reduction Techniques for LTE," TR 36.881 V14.0.0, June 2016.
[11] M. Lauridsen *et al.*, "Coverage and Capacity Analysis of LTE-M and NB-IoT in a Rural Area," *Proc. IEEE VTC-Fall 2016*, Sept. 2016, pp. 1–5.
[12] H.C. Nguyen *et al.*, " A Simple Statistical Signal Loss Model for Deep Underground Garage," *Proc. IEEE VTC-Fall 2016,* Sept. 2016, pp. 1–5.
[13] Nokia, "LTE-M — Optimizing LTE for the Internet of Things," white paper, 2015.
[14] A. Colazzo, R. Ferrari, and R. Lambiase, "Achieving Low-Latency Communication in Future Wireless Networks: The 5G NORMA Approach," *Euro. Conf. Networks and Commun.*, June 2016, pp. 1–5.
[15] G. Pocovi *et al.*, "Signal Quality Outage Analysis for Ultra-Reliable Communications in Cellular Networks," *Proc. IEEE GLOBECOM Wksps.,* Dec. 2015, pp. 1–6.

Biographies

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Troels B. Sørensen received his Ph.D. degree in wireless communications from Aalborg University in 2002. Upon completing his M.Sc. degree in electrical engineering in 1990, he worked with a Danish telecom operator developing type approval test methods. Since 1997 he has been at Aalborg University, where he is now an associate professor in the WCN section. His current research and teaching activities include cellular network performance and evolution, radio resource management, and related experimental activities.

Preben Mogensen received his M.Sc. and Ph.D. degrees from Aalborg University in 1988 and 1996, respectively. Since 2000, he has been a professor at Aalborg University and now leads the WCN section. He has co-authored more than 400 papers in various domains of wireless communication. Since 1995 he has also been associated part time with Nokia, currently as a principal engineer at Nokia-Bell Labs Aalborg. He became a Bell Labs fellow in 2016. His current research focus is on 5G, IoT, and ultra-reliable low latency communication for CPS.