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Mobility Performance in Slow- and High-Speed LTE Real Scenarios

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Abstract—Mobility performance and handover data interruption times in real scenarios are studied by means of field measurements in an operational LTE network. Both slow- and high-speed scenarios are analyzed by collecting results from two different areas: Aalborg downtown and the highway which encircles the same city. Measurements reveal that the terminal is configured by the network with different handover parametrization depending on the serving cell, which indicates the use of mobility robustness optimization. Although the network is dominated by three-sector sites, no intra-site handovers are observed in the city center as cells on the same site often cover different non-crossing street canyons. Moreover, no handover failures are experienced in the measurements which confirms robust LTE mobility performance. The average interruption time, which is at least equal to the handover execution time, lays within a 24-29 ms interval. Nevertheless, examples of delays larger than 100 ms are occasionally observed. The studied scenarios are replicated in a system level simulator to investigate whether simulations are capable of reproducing similar mobility performance.

I. INTRODUCTION

Today's Long Term Evolution (LTE) systems implement the so-called *break before make* handover mechanism, where the User Equipment (UE) breaks data exchange with the serving cell after receiving the handover command, resulting in temporary data interruption at every cell change. Some measurements performed in [1] conclude that, in the 95 % of the cases the device performs an intra-frequency handover, it experiences a detach time of 50 ms while in [2], times below 40 ms are found. After estimating an interruption time of 55 ms by means of measurements in a lab, [3] proposes synchronous Random Access Channel (RACH)-less handover procedures to reduce this time. Additionally, [4] suggests a stochastic model for estimating handover interruption times supported by field measurements, finding delays out of the usual range provided by the literature.

Although these gaps in the data-link have a minimal impact on the user experience in most of the multimedia and voice applications, the new *Traffic Efficiency and Safety* scenarios for future wireless systems, envisioned in [5], will require higher reliability constrains and lower latencies than the ones the current communications systems are able to provide. As a result, large handover data interruption times may compromise the requirement of providing a reliable exchange of information with less than 5 ms end-to-end latency, especially in scenarios affected by a large amount of handovers like high-speed scenarios.

The present paper analyzes intra-frequency mobility performance by field measurements in an operational 4G network. The experienced handover execution time and its associated data interruption time is observed for low and high mobility. To the best of our knowledge, previous studies do not distinguish between slow- and high-speed scenarios when analyzing handover delays. To this end, two different urban scenarios are considered: the downtown area of the city of Aalborg, Denmark, and the stretch of the highway which encircles the same city.

The experimental mobility results are, furthermore, used to verify the validity of the performance results obtained from our dynamic system simulations. Hence, the measurement scenarios are reproduced in our simulator including the same drive test routes. Simulation results and field measurements are afterwards compared to check how well the simulator reproduces real-life LTE performance. A similar study for 3G was reported in [6].

The paper is organized as follows: Section II describes the considered handover timing and the observed Key Performance Indicators (KPIs), while Section III presents the characteristics of each scenario. Section IV describes how measurements have been conducted, and the experimental results are shown in Section V. Simulation methodology, as well as a comparison between measurements and simulations results, are discussed in Section VI. Finally, Section VII summarizes the concluding remarks.

II. HANDOVER TIMING AND KEY PERFORMANCE INDICATORS

Figure 1 shows the handover procedure in LTE. It is a network controlled and UE assisted mechanism, where the UE is configured to send measurement reports to the serving cell according to certain triggering criteria.

Upon receiving the *Measurement Report*, the source cell sends the *Handover Request* to the target cell, which decides whether the UE can be accommodated or not (*Admission Control*). The decision is then communicated to the serving cell by means of the *Handover Request Acknowledgment*. The serving cell furthermore indicates to the UE that the handover can take place by the *Handover Command*, known as the *Radio Resource Control (RRC) Connection Reconfiguration* message. The elapsed time between the moment the UE sends the *Measurement Report* and the moment it receives the *Handover*

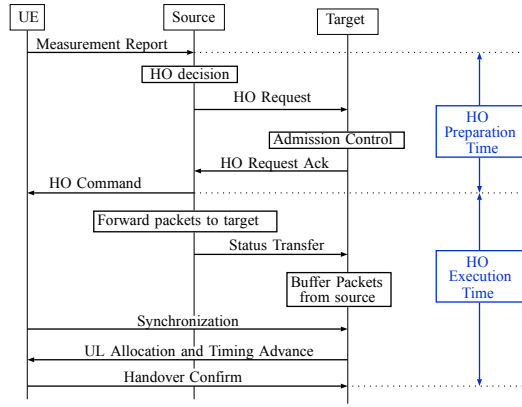


Fig. 1. Definition of the handover preparation and execution times.

Command is defined as the handover preparation time. After receiving the *Handover Command*, the UE detaches from the serving cell and initiates the synchronization phase with the target. Data communication is interrupted during this time and is not restored until the UE sends the *Handover Confirmation* or *RRC Connection Reconfiguration Complete* message. The time interval between both RRC messages is referred to as the handover execution time. In these studies it is assumed that the data interruption time is equal to the handover execution time. However, it typically takes around 5 ms from the time when the UE transmits the *RRC Connection Reconfiguration Complete* message until the target eNB starts scheduling data for the UE [3]. Hence, the data interruption time is slightly larger than the handover execution time.

In addition to the handover timing, other KPIs will be also considered in these studies such as: average number of intra- and inter-site handovers, number of Radio Link Failures (RLFs) and rate of Handover Failures (HOFs), as defined in [7]. Coverage is also analyzed by recording the Reference Signal Received Power (RSRP) during the drive tests.

III. SCENARIO DESCRIPTION

Low and high mobility performance is studied by analyzing two different scenarios of the city of Aalborg: The city center and a stretch of a highway. The analysis is performed under an operational LTE macro network deployed at 1800 MHz with 20 MHz channel bandwidth.

1) *City Center*: The network in this area consists of 29 macro sites with an average Inter-Site-Distance (ISD) of 741 m

and antenna heights that vary from 15 m to 60 m. Although the majority of the sites have 3 sectors, some of them count with 2 or even 4 sectors. Whereas the entire urban scenario measures 5450 m x 5335 m, the results are collected in a smaller observation area of 800 m x 1200 m. The area is surrounded by buildings of an average height of 4 stories. Some open areas such as parks, squares and a fjord can be also found. The scenario characteristics are summarized in Table I.

2) *Highway*: High-speed mobility performance is studied by analyzing the 8.5 km stretch of the E-45 highway that encircles the city of Aalborg. Wider open areas than in the city center can be found in this scenario, as well as, an immersed tunnel of 582 m length. The network of this area is characterized by 13 macro sites with 2 or 3 sectors and an average ISD of 1092 m. The average antenna height is 31.3 m. Scenario information can be found in Table II.

IV. MEASUREMENTS

Drive test campaigns are performed along selected routes on each scenario. For the City Center, four drive tests are conducted at an average speed of 15 kmph whereas, in the Highway scenario, a total of eight drive tests are performed: four at an average speed of 80 kmph and four at 100 kmph. While the drive test in the City Center is defined by a closed path, the measurements in the Highway are taken in both directions: from starting point A to an ending point B, and vice-versa. The terminal used in the measurements is a Samsung Galaxy S-III, LTE capable, forced to work at 1800 MHz. The UE is classified as *Category 3*, meaning that it supports a maximum data rate of 100 Mbps in the down-link. The device is programmed to periodically download a 100 MB file from a FTP server. The position of the UE is recorded using the Global Position System (GPS). Proprietary software installed in the phone allows to extract the RRC messages exchanged between the UE and the serving cell, as well as information about the physical cell ID, RSRP, Reference Signal Received Quality (RSRQ), Received Signal Strength Indicator (RSSI) and experienced Physical Downlink Shared Channel (PDSCH) throughput. RRC messages analysis is done to extract the mobility parametrization of the network in both scenarios. This mobility parametrization has been taken into account during the simulation phase.

TABLE I
AALBORG CITY CENTER SCENARIO PARAMETERS

Parameter	Value
Total scenario area	5450 m x 5335 m
Number of cells	88
Number of sites	29
Average antenna height	30.8 m
Antenna height std. deviation	13 m
Average antenna tilt	3.9°
Average tilt std. deviation	2.4°
Average ISD	741 m
Minimum ISD	308 m

TABLE II
AALBORG E-45 HIGHWAY SCENARIO PARAMETERS

Parameter	Value
Stretch length	8.5 km
Number of cells	23
Number of sites	13
Average antenna height	31.3 m
Antenna height std. deviation	13.22 m
Average antenna tilt	2.1°
Average tilt std. deviation	1.6°
Average ISD	1092 m
Minimum ISD	624 m

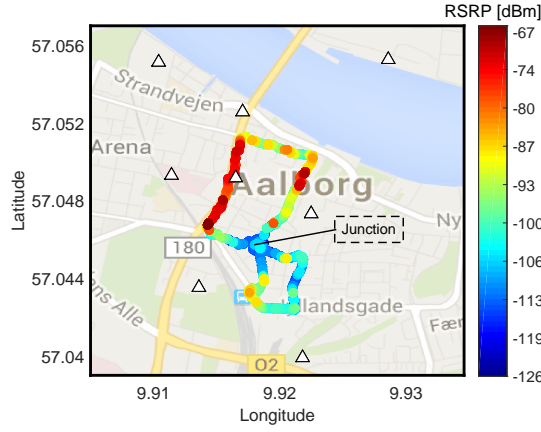


Fig. 2. Zoom into the observation area of the Aalborg City Center scenario. Base station locations depicted as white triangles. Measured RSRP during drive tests is shown in a color scale. This drive test path has been also analyzed in a 3G study in [6].

V. EXPERIMENTAL RESULTS

A. Coverage

Figure 2 and Figure 3 show the observation area and the network layout of each scenario together with the measured RSRP during the drive tests. As it can be observed in Figure 2, high RSRP is experienced in areas where the network is more dense whereas low values are found around the highlighted junction (intersection Boulevarden with Danmarksgade), as it was previously concluded in [6]. Nevertheless, levels are sufficiently high to maintain connectivity during the whole drive test. On the other hand, the coverage along the Highway is more uniform as only few locations with low RSRP levels are found. Although no data is recorded while driving through the immerse tunnel due to GPS signal loss, the coverage is generally good inside the tunnel and the connection is never lost.

B. RRC Messages Analysis

The RRC message analysis shows that the UE is configured by the network to send the *Measurement Report* both periodically and event-triggered. These reports may include a list of neighboring cells, their measured RSRP and RSRQ values, the event used for triggering handovers and the corresponding target cell. The configuration is done through the *Measurement configuration* field included in the *RRC Connection Reconfiguration* message which also contains information about which carriers and Radio Access Technologies (RATs) should be measured. Figure 4 shows the measurement configuration extracted during the drive tests. By analyzing the *Measurement Report* prior to each Handover Command it can be identified that handovers at 1800 Mhz are triggered by the commonly used A3 event (*measID* 1, *measObjectID* 1, *ReportConfigID* 1). The *RRC Connection Reconfiguration* message also provides information about the RRM measurement, which in this case is RSRP, and the values of the handover parameters: time-to-trigger (TTT) and offsets.

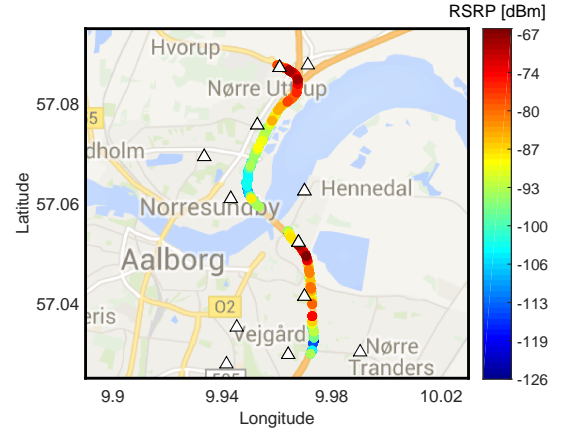


Fig. 3. Zoom into the observation area of the Highway E-45 scenario. Base station locations depicted as white triangles. Measured RSRP during drive tests is shown in a color scale.

From the message analysis, it is discovered that the A3 offset and hysteresis remain constant and equal to 2 dB respectively, while the TTT varies from cell to cell. Three TTT values are found distributed among the cells of each scenario: 320, 1024 and 1280 ms. The use of different handover event configuration for different cells indicates the use of Mobility Robustness Optimization (MRO) at the network. MRO essentially tunes the handover parameters in coherence with the characteristics of different cell boundaries. A larger value of the TTT tends to postpone handovers, while the short TTT results in faster and more aggressive handover. The use of MRO helps eliminating HOFs. Figure 5 shows the distribution of the TTTs found during the measurements. Notice that, although the City Center scenario consists of 88 cells, only 17 are discovered by the phone. On the other hand, the phone reports measurements from all cells in the Highway. An interesting fact is that the cell in the City Center scenario with a larger TTT is the one located on the other side of the

measID	measObjectID	measObjectID	measObject	carrierFreq
	reportConfigID	1	measObjectEUTRA	1850
1	1	1		
2	1	2		
4	1	4		
9	1	3		
		ReportConfigID	reportConfig	Event
		1	ReportConfigEUTRA	A3
		2	ReportConfigEUTRA	A5
		3	ReportConfigEUTRA	Periodic
		4	ReportConfigEUTRA	A2

Fig. 4. UE measurements configuration recorded during the drive tests.

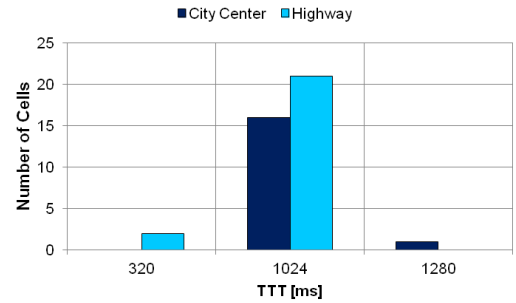


Fig. 5. TTT distribution among the discovered cells by the phone during the measurements for each scenario.

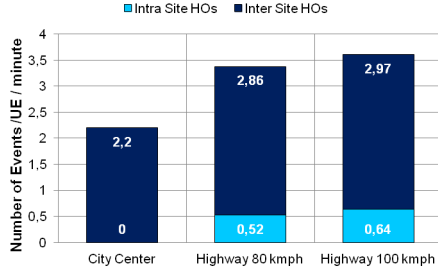


Fig. 6. Average number of handovers per UE per minute obtained in the measurements for both scenarios.

fjord compared to where the drive tests are performed.

C. RLFs and HOFs

Upon detection of physical layer problems, the UE starts the timer T_{310} . If better radio conditions are not experienced and T_{310} expires, a RLF is declared. Afterwards, the UE attempts the re-establishment and if it does not succeed in a period of time T_{311} , the UE goes to RRC idle mode. HOF is declared if a RLF occurs during the handover process.

From the RRC messages analysis it is found that the timer T_{310} is parametrized with a value of 2 s. This large value assures that the UE has enough time to get back in synchronization after experiencing bad radio conditions and hence, avoiding RLF declaration. Furthermore, the timer T_{311} is found to be 3 s. Measurements revealed that neither RLFs or HOFs are experienced in any of the scenarios, even though some areas with low RSRP levels are found.

In order to confirm that our method for checking RLFs and HOFs is valid, a simple experiment to force a RLF was conducted before the drive tests. After setting the configuration for performing a download, the phone was wrapped in aluminum foil, replicating a scenario in which the UE experiences a signal drop. Analyzing the RRC messages, it was observed that following the wrapping of the phone, the device sends an *RRC Connection Re-establishment Request* message with the value *OtherFailure* in the cause field. At this point, if the phone is unwrapped before the timer T_{311} expires, the connection is successfully re-established. However, maintaining it wrapped for a longer time, causes the phone to go to idle mode after the T_{311} expiration.

D. Handover Events and Timing

Figure 6 shows the average number of measured handover events per user per minute split into inter- and intra-site handovers. As expected, the number of handover increases with the speed. However, although the UE velocity is a factor 5-7 higher in the highway scenario as compared to the city center, the handover rate is only a factor 1.5-1.6 higher for the highway case. The larger ISD in the highway is the reason for not experiencing higher relative handover rates, as compared to the city center. The chosen drive path and the location of the sites with respect to the streets layout play an important role in these studies. The street canyon effect makes the signal from far sites to dominate over closer sites. Thus, no intra-site

TABLE III
MEASURED HANDOVER TIMES DURING THE DRIVE TESTS.

Scenario	Average Times [ms]		Median Times [ms]	
	HO Prep.	HO Exec.	HO Prep.	HO Exec.
City Center	48.2	28.9	39.0	26.0
E-45 80 kmph	39.2	26.1	36.0	26.5
E-45 100 kmph	44.7	24.5	38.0	24.0

handovers have been recorded in any of the measurements in the City Center. In connection to this, it is worthy to highlight that due to Line Of Sight (LOS) conditions, the site located at the other side of the fjord is the main dominant in this observation area. Moreover, the TTT assigned to this particular cell, larger than the one in the neighbors, makes it more difficult for the UE to connect to this server. Although the presence of wider open areas explains the existence of intra-site handovers in the drive tests for the highway, the inter-site events are still dominant in this scenario.

Table III shows the average handover times experienced during the drive tests. As some of the times are found to be in the region of hundreds of milliseconds, the median values are also shown to avoid a possible bias in the results. The recorded latency values in the City Center are generally higher than in the Highway scenario due to presence of inter-site handovers only. Nonetheless, the predominant number of inter-site events in both scenarios makes the median values similar in all the cases. On average, it takes a total time of 77 ms to perform a handover in the City Center whereas, in the Highway, it takes 65 and 69 ms when driving at 80 and 100 kmph respectively. The measured average handover execution time –and its associated data interruption time– corresponds to 28.9 ms in the City Center, 26.1 ms in the Highway while driving at 80 kmph and 24.5 ms at 100 kmph. The average number of handovers experienced in the City Center is 16.5, while in the Highway are experienced 24.9 and 21.3 handovers at each speed. From these numbers, and considering that it takes 450 s to travel the observed urban path and 444 s and 354 s to transverse the segment of the E-45 at 80 and 100 kmph respectively, it can be calculated that the phone was able to transmit or receive data the 99.8 % of the time.

Figure 7 depicts the empirical Cumulative Distribution Function (CDF) of the extracted handover preparation and execution times. While the lower tail of the plot reaches a few milliseconds, it can be observed that the 5 % of the cases, the handover execution time is higher than 55 ms for the City Center, reaching extreme values of more than 100 ms. This can be due to the back-haul latency, load conditions in the target cell, and the Random Access procedures during the *Synchronization* phase. These large values may compromise the requirements, in terms of latency and reliability, for future real-time applications.

VI. MEASUREMENTS AND SIMULATIONS COMPARISON

To verify whether our simulator is able to reproduce results in coherence with the measurements, the site-specific scenarios

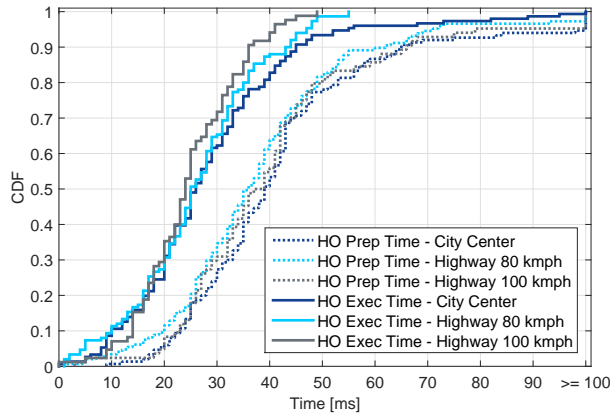


Fig. 7. CDF of the handover preparation and execution times obtained during the measurements for both scenarios.

are simulated under a dynamic system level simulator which implements the majority of the RRC connected mode mobility mechanisms defined by the 3rd Generation Partnership Project (3GPP) for LTE, including terminal physical-layer measurements, Layer-3 filtering and reporting events. The simulator has been utilized in several mobility studies, for 3G and 4G, involving 3GPP ([7], [8]) and site-specific scenarios ([6], [9]).

Mobility parametrization discovered by the measurements and the network information provided by the operator are taken into account to align simulations with measurements. Scenarios are modeled by using a three-dimensional map of the city. Signal propagation is predicted by path loss maps computed using state-of-the-art ray-tracing techniques based on the Dominant Path Model (DPM) [10] and calibrated following recommendations from [11]. As each path loss map has a resolution of $5\text{ m} \times 5\text{ m}$, radio propagation conditions are considered constant within a 25 m^2 area. More details on the simulation methodology and scenario modeling can be found in [6]. Each scenario is simulated separately and statistics are only collected within certain observation areas. All cells outside the observation areas are considered to be fully loaded, generating constant interference. The City Center scenario is simulated at 15 kmph while the Highway is simulated at 80 and 100 kmph.

Initial analysis of the first order statistics from the simulations show a promising match with the measurements. Like in the experimental results, inter-site handovers are found to be dominant, and the probability of experiencing RLFs and HOFs is close to zero in the simulations. Additionally, simulations are able to point out most of the locations where the handovers happen in the field. Nevertheless, the obtained handover rate is slightly larger in the simulations compared to findings from the field trials. The latter is mainly explained by the $5\text{ m} \times 5\text{ m}$ resolution of the ray-tracing propagation data in the simulator, and the lack of modeling dynamic effects such as e.g. drive-by vehicles that temporary blocks dominant radio paths to some cells. Despite not experiencing a 100% match between measurements and simulations, our study indicates that the followed modeling methodology is suitable for reproducing

real-life effects to a large extend. Nevertheless, a deeper comparison including more statistics are needed.

VII. CONCLUSIONS

Mobility performance and handover timing for site-specific scenarios are studied in this paper by means of drive tests measurements and system level simulations. Field measurements are performed in an operational LTE network in the metropolitan area of the city center of Aalborg, Denmark, to study slow mobility at 15 kmph. Additionally, high mobility is analyzed in the highway which encircles the city, at speeds of 80 and 100 kmph. Experimental results show that although the average measured data interruption time is found to be, at least, between 24 and 29 ms, some extreme values higher than 100 ms are found. These high delays may compromise the requirements for future traffic and safety applications. The number of handovers are found slightly higher in the simulations than in measurements. Nevertheless, simulations are able to indicate that the scenarios are affected by a high number of inter-site handover and high handover delays.

As future work, it is recommended to further investigate the handover timing in real networks (e.g., for a given back-haul latency, to study how the load conditions in the target cell may modify the handover delay). Moreover, it is also suggested to explore solutions to decrease the handover interruption time considering latency and reliability requirements for future 5G applications.

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