Field Measurement for Antenna Configuration Comparison in Challenging NLOS Locations

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Abstract — *This article has two main objectives. First, it describes the practical challenges of field trials and proposes a developed test method. Secondly, the test method is used to compare uplink performance with different antenna technologies when user equipment does not have a line of sight to the evolved Node B. Both passive and active antenna configurations were used in the performance evaluation. Modern cellular networks have high demands for capacity, reliability, and availability. The verification of a network's configuration and technological features is essential to guarantee network performance, and the performance of a network must be verified by laboratory testing or field trials; such trials produce experimental knowledge of technology features and configurations. Technological and environmental factors must also be considered before performing mobile network field-testing. Our work showed that moving user equipment produces more reliable and repeatable results than measurements with stationary user equipment. Our antenna configuration comparison study revealed that in the uplink direction, active antenna system beam control could significantly increase the uplink capacity in non-line-of-sight conditions.*

Index Terms— 2- and 4-way RX diversity, AAS, field trial, horizontal beamforming, non-line-of-sight environment, MIMO, uplink capacity improvement, vertical beamforming.

I. Introduction

This paper illustrates the practical challenges of measuring dynamic cellular networks. This study describes a field test method developed for antenna systems. Many of the recent research activities relating to emerging 5G related testing is concentrating methods based on emulating realistic electromagnetic environment such as [1-3]. However, as stated in [4] the measurements in an actual operating environment is required to fully cover and compensate the antenna configuration selections. Therefore, we focus on the field measurements and the objective of this paper is to introduce a drive test method and comparison of uplink (UL) performance with different antenna technologies when receiving non-line-of-sight (NLOS) signals in field tests. The antenna configurations used included both a passive and an active antenna system (AAS). A radiation pattern can be controlled horizontally by changing its azimuth angle and vertically by changing the tilt angle of the antenna. AAS includes a flexible configuration that consists of diversity beams and other features for beam control to improve throughput [5]. The field trial benefitted 2-way and 4-way receiver (RX) diversity in both antenna systems. The field trial environment consisted of three macrocellular long-term evolution (LTE) evolved Node Bs (eNBs) operating in the 2.1 GHz band. This trial environment had two AAS's and one passive antenna system used for the measurements. The environment could encompass one macro cell. With vertical control, it was possible to add an additional beam, while with horizontal control, it was possible to steer the main beam towards the user equipment (UE). In field trials, the mobile network user had UE in drive testing to evaluate the network quality from a mobile device's point of view. The field trial results indicated that AAS beam control could achieve remarkable capacity gain in the uplink direction when the UE did not have a line of sight to the eNB.

The remainder of the article is organized as follows: Section II illustrates aspects that affect mobile networks performance including some related works of the antenna configuration-related field measurements. The measurement setup and environment of our field measurement campaign are described in Section III. Selection of the measurement points is explained in Section IV, and the description of the measurement case is shown in Section V. Section VI focuses on the analysis of the measurement option, i.e., the comparison of stationary and moving measurements, which was recently presented in [6]. The actual key results of the antenna configuration comparison via field measurements are shown in Section VII, and the discussion and conclusion are presented in Section VIII.

II. Factors Affecting Performance and Field Measurement in Mobile Networks

Several factors must be considered when verification

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measurements of a mobile network are planned; the mobile network and system parameters need specific attention. Environmental factors significantly impact signal propagation. When measurements are planned, they often demand additional definition afterwards.

A. LTE Technology

LTE capacity depends on many issues, such as the data transmission capability of single cells. The mobile network and parameters need to be designed appropriately to obtain optimal coverage and capacity. Network parameters such as radiated power, frequency band, bandwidth, antenna design, and power need to be considered. The capacity is closely dependent on the number of LTE eNB elements and the bandwidth each eNB offers. The distance between the eNB and the UE also affects the capacity. The dynamic modulation and coding scheme results in high data rates and capacity when the UE is located near the eNB, whereas the cell edge and inside building locations offer minimum capacity. As the bit error rate increases along with the utilization level of the network, it also influences the signal coverage areas of the eNBs [7].

B. Multiple-Input Multiple-Output Technology and Antenna Arrays

Multiple-input multiple-output (MIMO) is a radio communications technology that simultaneously utilizes multiple spatially distributed antennas. These multiple antennas act as transmitters (TX) and receivers (RX), which enable a variety of different signal paths for each antenna (see Fig. 1). This enables multiple signal paths to be utilized to transmit the data. MIMO antennas can use spatial diversity and spatial multiplexing formats in data transmission. Spatial diversity improves the signal-to-noise ratio and thus improves reliability [8]. Spatial multiplexing provides an increase in data throughput by utilizing different paths to transmit the data traffic.

The antenna configuration is a very important factor in the channel capacity of modern cellular networks. The special effect of antenna arrays in mobile communications is discussed in [9], which emphasizes the possibility of two arrays in a scattering environment to create parallel channels, and thus, in effect, to act as many independent antennas at the same time, carrying much more traffic over the same bandwidth.

To fully understand and compensate the antenna arrays, several calibration procedures are suggested by [4]. Beyond the calibrations performed in an anechoic chamber, measurements in particular cases in an actual operating environment have been proposed to compensate for the influence of the site and propagation channel and to update the coefficients of the antenna calibrations.

C. Field Measurements of Antenna Array Effects

Field experiments on antenna configurations associated with a downlink mobile network are studied in [10]. The authors compare four antenna configurations, i.e., co- and cross-polarized antenna arrays with array treatment and space diversity. In their experimental results in an urban area consisting mainly of NLOS conditions, the MIMO had only a limited effect, and the space diversity option resulted in higher throughput.

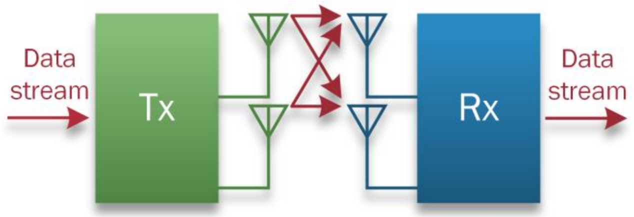

Fig. 1. MIMO concept.

Another field experiment of the channel capacity measurement on an actual cellular network with the usage of different antenna configurations was conducted by Nishimori et al. [11]. They concluded and confirmed that the most effective antenna configuration changes were based on the signal-to-noise ratio (SNR) or the number of antennas at the base station. This result convinces us of the need to investigate antenna configurations, i.e., the proper selection in challenging NLOS conditions with a low SNR value.

D. Environmental Impacts on Signal Propagation

The environment affects signals in many ways, depending on the surroundings. In line-of-sight (LOS) signal propagation, there are no obstacles between transmitter and receiver. A multipath causes the largest effect, which can be destructive or constructive. Obstacles such as buildings and vehicles around UE produce reflections and multipath propagation. Each path has a specific delay, attenuation, and phase-shift feature. The signal attenuates on the way from the transmitted antenna to the receiver because the signal energy spreads around the transmitter. The UE receives and sums up multiple copies of the signal with different phases and amplitudes. Arriving signals have a random phase difference and thus may gain or attenuate each other. Buildings will cause losses that are dependent on the electrical properties of the materials [12].

There have been practical studies of energy-efficient construction practices that have effects on RF signals by increasing entry losses [13]. The roughness of surfaces fluctuates the power of scattering waves, depending on the frequency of the incident wave [12]. The environmental effect of trees has also been widely studied. Many studies [14-16] report a seasonal effect, i.e., an increase in the attenuation of trees in-leaf compared with the out-of-leaf state.

E. Weather Impact on Signal Propagation

Effects of weather on signal propagation are mainly related to attenuation by atmospheric gasses and rain. Oxygen and water vapor in the atmosphere cause strong absorption at resonance frequencies. However, such frequencies are above 10 GHz; atmospheric gas absorption at frequencies below 10 GHz is lower than 0.01 dB/km, and its effect can be ignored [17].

Rain affects radio wave propagation in many ways. The main effect is the attenuation of the radio signal caused by the absorption of power by water droplets. There is also a loss of power of the signal between the transmitter and receiver due to the scattering of the water droplets.

Water droplet diameter ranges from fractions of millimeters in cases of light rain to some millimeters in heavy rain. Consequently, it is possible to use the Rayleigh model to evaluate the absorption and scattering of droplets up to several GHz [18].

Conducted studies showed that the attenuation is lower than a 0.1 dB/km frequency up to 10 GHz in cases of moderate rain (5 mm/h), while at 5 GHz, the attenuation is also lower than 0.1 dB/km in cases of heavier rain (20 mm/h). Regarding the scattering, its effect is small compared to that related to power absorption. The depolarization effect is also small [19]. Consequently, at ultra-high frequencies (UHF), rain does not significantly affect signal propagation [20].

Water is also present in fog. However, fog droplets have radii on the order of 1/100 mm, producing a negligible absorption in UHF.

Finally, it is worth noting that rain can also affect the signal in an "indirect way," changing the electromagnetic environment. In fact, wet surfaces have reflective properties different from those of dry surfaces. Since the electromagnetic environment depends on the reflecting properties of the surfaces, wet surfaces modify the multipath propagation and, hence, the communication channel between transmitter and receiver.

III. MEASUREMENT ENVIRONMENT AND SETUP

A. *Technology Solutions*

All trial network antennas employed RX cross-polarization diversity in addition to polarization diversity; passive antennas using two columns also employed spatial diversity. Different UL beamforming solutions were operated in this field trial to compare their performance in an NLOS situation. Usually, RX signals to eNBs arrive through various paths such as direct LOS, reflections, and dispersions. The RX diversity technique is used to improve communication in an NLOS situation. RX diversity means using two or more receiving antennas, and it is usually implemented as part of spatial diversity, polarization diversity, or a combination thereof. The signals from the antennas are combined in the receiver, and a sensitivity gain is achieved. The aim of beamforming is to increase the coverage of the cell.

In this field trial, the vertical beamforming used a main beam and an additional beam, separated by applying a different tilt angle. In the horizontal beamforming, the beam was steered towards the UE. The beamforming methods are shown in Fig. 2.

B. *Network*

Measurements were performed in a suburban/rural environment within the field trial environment, located in Ylivieska, Finland [21]. The field trial environment was developed within the CORE, CORE+, and CORE++ projects between 2011 and 2016. The AAS environment was part of a cognitive radio trial environment (CORE) that was operated to showcase the world's first live licensed shared access (LSA) trials, described in [22]. This environment has also been used in several other public trials, such as [23, 24]. The field trial environment network has a restricted connection to the Internet or other public networks. This environment can be operated only by the UEs acquired for the test purpose. The field trial network is illustrated in Fig. 3 and described in [6, 25]. The data traffic for testing was provided by file transfer protocol (FTP) from UEs to the network and, more specifically, by the FTP server located in the Nokia Networks core network in Oulu. Table I presents the test parameters for each antenna configuration in this trial. The Puuhkala site operated two AAS and one passive antenna in the 2.1 GHz LTE band. The only variations occurred when the antenna height varied between 154 and 155 meters. The antenna height was based on the global positioning system (GPS) information.

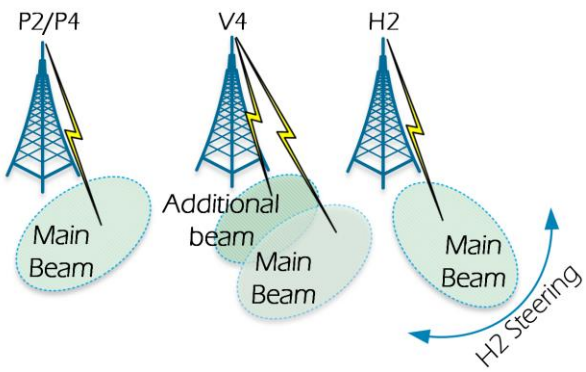

Fig. 2. Different antenna configurations in trial environment.

C. *Measurement Tools*

Drive test software [26] was operated with the measurements to evaluate performance. During the test, a test car was driven very slowly, parallel to NLOS point buildings. The car was equipped with the drive test software, an LTE dongle [27], a test SIM card, and external antennas [28] that minimized the effects from the vehicle's structure. A laptop with the measurement software was located on the front seat of the car (Fig. 4). The transmitting antenna was located on

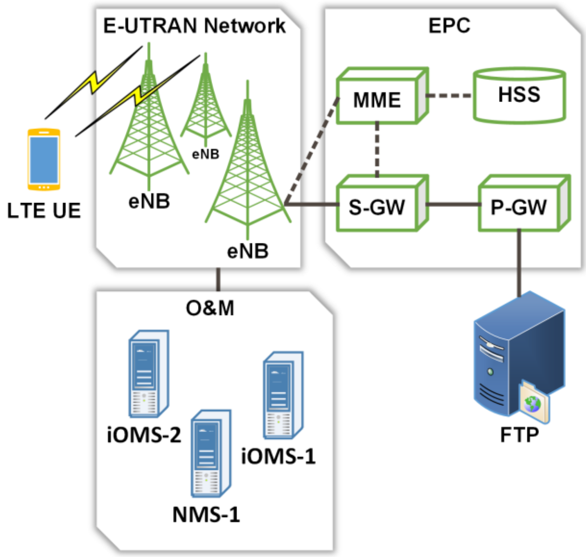

Fig. 3. Field trial network.

TABLE I.
TEST PARAMETERS

Configuration	**LTE FDD AAS 2100 Vertical Single Column**	**LTE FDD AAS 2100 Horizontal Four Column**	**LTE FDD Passive 2100 Two Column**
LTE system Bandwidth	5 MHz		
Carrier band	2100 MHz (LTE band 1)		
Beamwidth (°)	59	30	64
eNB max TX power	43 dBm		
Antenna height from GPS info	154 m	155 m	154 m
Number of mobile UEs	1		

the roof of the car and the RX only antenna on the dashboard of the car. The LTE dongle used single-carrier FDMA (SC-FDMA) in the uplink direction. When the channel state is evaluated several factors such as SINR, RSRP and throughput indicate the state [29]. During the measurements Key Performance Indicator (KPI) values such as media access control (MAC) throughput, reference signal received power (RSRP), transmit (TX) power, reference signal received quality (RSRQ) and signal-to-noise ratio (SNR) were gathered. Our analysis focused on throughput because our previous studies revealed that it is the most essential KPI to compare different antenna technology features. The tests were performed in a rather sparsely populated areas and the frequency used was on a loan from a national operator who does not use the frequency in the locations where the performance measurements were made, nor do other operators use the frequency and thus the interference from other users and systems is negligible. We verified interference impact by monitoring SNR. GPS was used to identify the location, and during the measurements, files were transferred by FTP.

D. Measurement Period

The conducted measurements took place from early June to late September. During the four-month measurement period, the only considerable changes in the measurement circumstances were that the environment foliage decreased in autumn, which caused a slight throughput increase in the measurements [25]. The weather was visually observed during the measurements, and it was established that weather had no effects on the results.

IV. Selection of the Measurement Points

At the beginning of this study, it was important to find the most suitable measurement points (MPs) with challenging locations that could provide meaningful information on the performance of a complex communication system. The procedure began by defining the specifications for challenging points between the UE and eNB. The objective was to find locations with a challenging radio environment. These points were chosen so the environment had NLOS signal propagation to the Puuhkala eNB. Eleven different measurement points were selected for the preliminary study, according to assumptions about challenging environments based on such aspects as surrounding buildings, the distance and direction from the antenna mast, and the estimation of the coverage area. The preliminary measurements provided more accurate information with which to plan the actual comparison measurements.

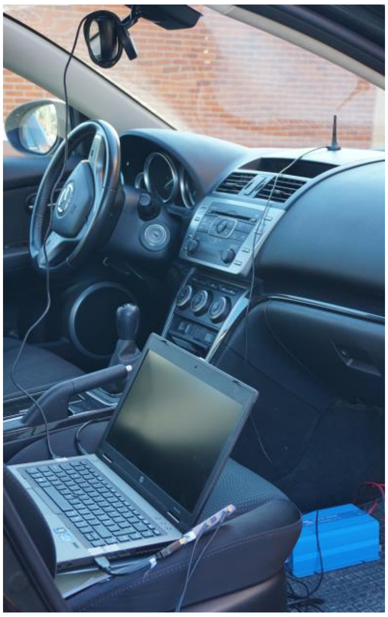

Fig. 4. Measurement setup.

A. Preliminary Measurements

The Puuhkala eNB (brown point: eNB) and measurement points are shown in Fig. 5. Three of the eleven measurement points were located indoors (blue points: MP 9, MP 10, MP 11). The remaining eight measurement points were located outdoors (red points: from MP 1 to MP 8). Common to the outdoor measurement points was that the material used in the surrounding buildings included mainly brick and concrete elements.

Two of the three indoor measurement points were located in the proximity of the Puuhkala eNB, and MP 11 was located inside Centria's campus. After the first preliminary measurements, it was concluded from the analysis that the indoor measurement points, MP 9, MP 10, and MP 11, did not meet the specific requirements for these measurements, because these measurement points produced exceptionally good UL throughput with every antenna configuration, even while the points were located inside concrete buildings. It was concluded that the good UL throughput was because these indoor measurement points were located near the Puuhkala eNB. The signal strength as well as signal-to-noise ratio was good, and it enabled the best possible UL throughput with these setups.

Outdoor measurement points MP 1, MP 2, and MP 3 were also too close to the eNB and produced the best possible UL throughput in the preliminary measurements. In the preliminary analysis, it was concluded that these measurement points did not meet the requirements set in the specifications for these measurements, since they did not offer a sufficiently challenging environment.

B. Accepted Measurement Points in Detail

Based on the analysis of the preliminary measurements, it was concluded that five measurement points—MP 4, MP 5, MP 6, MP 7, and MP 8—would be suitable for actual measurements. Most of these measurement points have high buildings obscuring the LOS from the Puuhkala eNB, and they also have neighboring buildings near them. The height difference between the Puuhkala eNB antenna element and measurement points MP 4 to MP 8 has been calculated in Table II. The height values of the eNB and MPs are based on GPS information. The distances from the measurement points

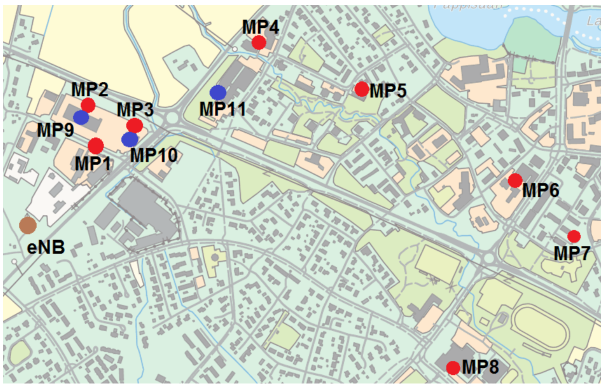

Fig. 5. Puuhkala eNB and MP 1 to MP 11 locations.

to the Puuhkala eNB and the height of the buildings obscuring the LOS at each measurement point are shown in Table II.

The building obscuring the LOS at MP 4 between the eNB and UE is a four-story office building whose outer wall is made of bricks. Behind this office building is a one-story office building with a very large cone-shaped roof. The yard has been coated with asphalt and serves as a parking lot for the workers.

At MP 5, the building between the eNB and the measurement point is a three-story apartment building whose outer wall is made of bricks. The yard of this building has been coated with asphalt. Behind this measurement point is an apartment building whose outer wall is also made of bricks. Near these buildings grow a number of birch and pine trees.

The building between MP 6 and the eNB is a community building whose outer wall is made of wood. This measurement point is located in the courtyard of the community building and a four-story office building. The office building and other buildings around this measurement point have outer walls made of bricks, and the courtyard is coated with asphalt. This courtyard has parking places for the workers' cars, and the area was almost full of them during the measurement.

The building between MP 7 and the eNB is a four-story apartment building whose outer wall is made of bricks. Near this building grow a number of birch trees. In the proximity of MP 7 is an asphalt parking space for the residents.

MP 8 has a tennis hall with an arched roof between the UE and eNB. In the immediate vicinity of the tennis hall are no other tall buildings. A few hundred meters from the tennis hall is an indoor ice rink. The asphalt-coated inner yard between the tennis hall and the indoor ice rink serves as a parking space.

V. Descriptions of Measurement Case

In the chosen measurement points from MP 4 to MP 8, repeatability, reliability, and good results in the challenging radio environment were investigated in the measurements. At each measurement point, the measurement began by placing the UE in a predetermined location, which was evaluated visually, and then the UL data transfer could be started.

One measurement data set lasted approximately one minute, during which time the drive test software gathered approximately two samples per second. During one measurement date set, on average, the number of throughput samples gathered was 150 ± 20. Ensuring reliability and repeatability of the results in each MP several different data sets were measured on different dates.

TABLE II.
MEASUREMENT POINT INFORMATION

Measurement points (MP)	Distance to Puuhkala eNB	Height of building obscuring LOS	Height difference between eNB antenna and the MP	RX Azimuth angle (°)
MP 4	830 m	18.5 m	57	-34°
MP 5	1014 m	14.5 m	60	-17
MP 6	1380 m	11.0 m	37	-2
MP 7	1547 m	12.0 m	56	4
MP 8	1271 m	10.0 m	47	23

A. Stationary Measurements

The UE (the car) was stationary during the first phase of measurements, i.e., the creation of several measurement data set on different dates. Measurement analysis indicated that the static UE measurements at the measurement points had too much variation on the date sets measured on different dates, and the results were not repeatable. This was due to the signal reflections of the environment changed over time due to the varying multipath propagation channel over the days and the difficulty of placing the UE at the exactly same spot for every measurement data set. It was concluded that the measurement procedure should be further developed to obtain statistical and reliable measurement results.

B. Moving Measurements

In NLOS conditions, the time variation of multipath channel conditions is evident and unavoidable. Many condition changes near the reception point cause changes on the summing of all the received signal strengths. Those changing conditions include the misplacement and disorientation of the measurement device affecting the signal path lengths, changes on the reflection coefficients of surrounding buildings due to change in surface moisture, placements and orientation of parked and moving vehicles and people near the reception point. Beyond near the reception point, the variation of the signal strength over the whole propagation path could be affected via changes on weather conditions or possible shadowing due to trees and foliage.

Thus, in NLOS conditions with stationary measurements repeated over the time, even a slight change or misplacement and disorientation of the measurement device are plausible sources of high variation between the received signal strengths and thus affecting the throughput results. The aim of moving measurements was to rid of that effect and to achieve results that are less vague and less a possible source of erroneous interpretation to the results of different antenna configuration comparisons. The measurements were repeated with moving UE. The car with the measurement equipment was driven very slowly, parallel to NLOS point buildings. The measurements were repeated forwards and backwards to see whether the direction of movement influenced the results. It appeared that the results were more reliable and repeatable when the UE was moving slowly.

VI. Comparison of the Measurement Method Options

We performed several moving and stationary measurements with different antenna configurations. In this section, we analyze the distributions of the measurements on different dates or at different times. When the measurement is reliable and repeatable, the distributions of different measurements should not differ much. In the first analysis, we calculated several boxplots. Since the difference between moving and stationary measurements was particularly high at points MP 5 and MP 6 for the V4 configuration, these sites/methods were further studied. The results for MP 5 were presented in [6], while here, we consider those for MP 6. An example boxplot is given in Fig.6. In Fig. 6 as well as later in Figs. 9 and 10, the box in the middle represents the

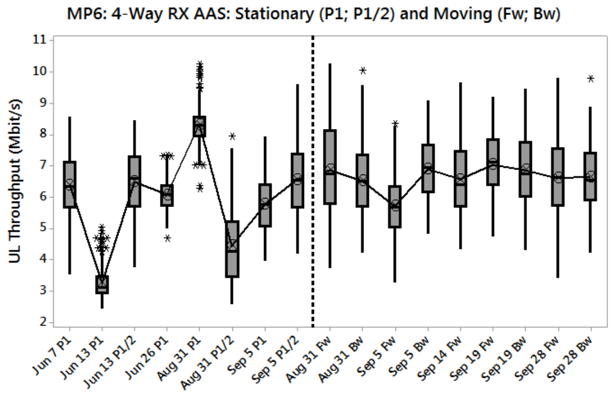

Fig. 6. Measured distribution at MP 6 with V4 configuration.

interquartile range (IQR) box, i.e. between 25 and 75 percentile. The median value is seen inside the box as a black line. The black circle with cross and the connecting line represents the average of all values. The ends of the whiskers can represent two possible alternative values: the minimum and maximum of all of the data without any outliers, or the lowest datum still within 1.5 IQR of the lower quartile, and the highest datum still within 1.5 IQR of the upper quartile. Data outside 1.5 IQR levels are discharged as outliers, which are shown as asterisks. The dispersion is also higher with stationary measurements. The smaller dispersion with moving measurement is an indication of a more repeatable measurement method, but as a side effect, the smaller dispersion also causes the few more extreme values to be interpreted as outliers in the boxplot analysis. The smaller box, i.e., the difference between the first and third quartiles, affects the smaller maximum length of the whiskers, meaning a tighter criterion for outliers.

As a second method, we used the analysis of variance (ANOVA) as well as some post-ANOVA visualization as shown in Fig.7 for MP 6. In a case of the stationary measurements, the mean values are more often considered as significantly different from each other compared with the moving measurements.

In the last statistical analysis, the similarities of the measurement distributions were pair-wise checked with a two-sample Kolmogorov-Smirnov test (kstest). The test returned a decision for the null hypothesis that data in two compared sample distributions came from the same continuous distribution. The result of the kstest was 1 if the test rejected the null hypothesis at the selected significance level and was 0 otherwise. We performed the pair-wise tests with Matlab at the 1% significance level. The results of pair-wise kstests for stationary (S1–S8) and moving (M1–M9) measurements are given in upper-right corner of Tables III and IV, respectively. The lower-left corner of these tables gives the actual uncertainty level, i.e., *p*-values of the tests. In the moving measurements, 63.9% of the non-diagonal different measurements led to the same distribution, while the rate was only 10.7% for the stationary measurements. These analyses clearly reveal the outperformance of the moving measurement method in producing reliable and repeatable results.

The results for the moving measurement were more reliable and repeatable, because in motion, the most extreme and deep fading due to reflections or other properties of the signal connection between the eNB and UE were averaged out. The more reflections there are, the better the connection is, because the technique used—the LTE single input multiple

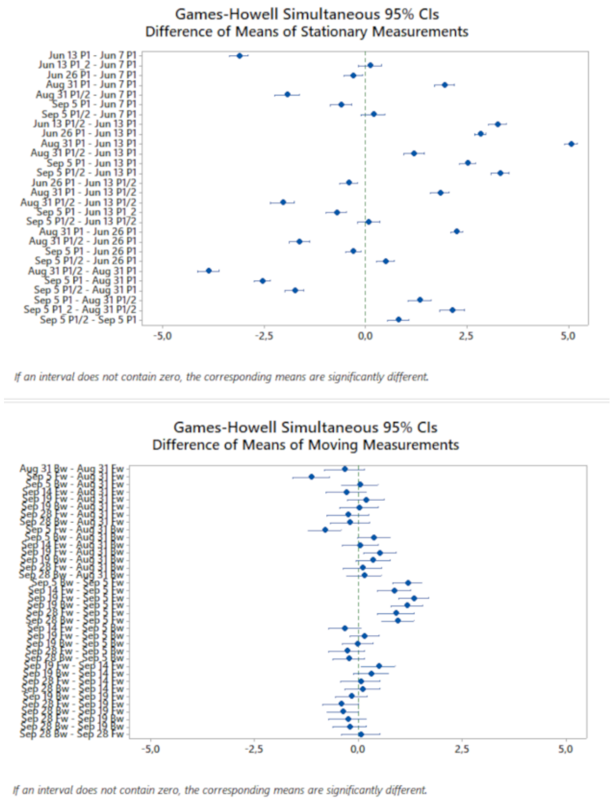

Fig. 7. Comparison of mean values for MP 6: upper graph with stationary measurement, lower graph with moving measurements

output (SIMO)—benefits from the fact that a considerable number of reflections appear as long as they are received by the eNB at sufficiently different times. Moving forward or backward makes no significant difference. This was noticed in the analysis of the measurement results.

VII. Results of Antenna configuration Comparison

In the configuration comparison, the UL performance was evaluated by gathering instantaneous throughput data from measurement results from the drive test software contained signal information, throughput, and several other values. The maximum throughput for the UL performance within the test network was 10.4 Mbit/s, while the theoretical maximum throughput for UL performance in the field trial network is 12.6 Mbit/s. After additional measurements and analysis,

TABLE III.
TWO-SAMPLE KOLMOGOROV-SMIRNOV TEST OF EIGHT STATIONARY MEASUREMENTS (S1-S8) AT MP 6

MP 6: V4 configuration at 0.01	Jun-01	Jun-13		Jun-26	Aug-31		Sep-05	
	S1	S2	S3	S4	S5	S6	S7	S8
S1	0	1	0	1	1	1	1	0
S2	<0.001	0	1	1	1	1	1	1
S3	0.057	<0.001	0	1	1	1	1	0
S4	<0.001	<0.001	<0.001	0	1	1	1	1
S5	<0.001	<0.001	<0.001	<0.001	0	1	1	1
S6	<0.001	<0.001	<0.001	<0.001	<0.001	0	1	1
S7	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0	1
S8	0.076	<0.001	0.654	<0.001	<0.001	<0.001	<0.001	0

TABLE IV.
TWO-SAMPLE KOLMOGOROV-SMIRNOV TEST OF NINE MOVING MEASUREMENTS (M1–M9) AT MP 6

MP 6: V4 at 0.01	**Aug-31**		**Sep-05**		**Sep-14**	**Sep-19**		**Sep-28**	
	M1	M2	M3	M4	M5	M6	M7	M8	M9
M1	0	1	1	0	0	0	0	0	0
M2	0.005	0	1	1	0	1	0	0	0
M3	<0.001	<0.001	0	1	1	1	1	1	1
M4	0.023	0.002	<0.001	0	0	0	0	0	0
M5	0.035	0.878	<0.001	0.016	0	1	0	0	0
M6	0.020	<0.001	<0.001	0.404	<0.001	0	0	0	1
M7	0.174	0.068	<0.001	0.423	0.039	0.180	0	0	0
M8	0.023	0.483	<0.001	0.136	0.664	0.020	0.272	0	0
M9	0.050	0.505	<0.001	0.095	0.710	0.003	0.169	0.822	0

Fig. 8. Puuhkala eNB and MP 4 to MP 7 NLOS measurement points.

MP 4–MP 7 (Fig. 8) were selected for throughput gain comparison. The average throughput value for each NLOS measurement point is found in Table V. We originally presented in [25] the results of comparisons that will be elaborated in this Section.

In the results, both the forward (Fw) and backward (Bw) moving UE samples have been combined, because it was found that there was no significant difference between the samples. Fig. 9 shows the similarities between the forward and backward sample results at the MP 6 point.

Measurements were conducted during the morning and midday hours. The repeated measurements indicate that the time had no effect on the results. During the testing period in late summer and autumn, shown in Fig. 10, the measurements indicate that a slight throughput increase could be found in some MP results when the environmental foliage decreased during late autumn. This effect is expected as many studies have reported the decrease of the attenuation of trees without foliage e.g. [11-13]. The most notable changes in the measurement results can be found at MP 7; in early

TABLE V.
THROUGHPUT IN MP 4 to MP 7

Location	**Configuration**				
	P2	**P4**	**V4**	**H2**	**H2 steering**
MP 4 (Mbit/s)	5.51	7.57	8.11	2.09	**8.57**
MP 5 (Mbit/s)	3.91	5.77	**7.32**	3.00	6.94
MP 6 (Mbit/s)	4.08	5.49	**6.60**	5.65	
MP 7 (Mbit/s)	3.90	5.55	**6.08**	4.87	

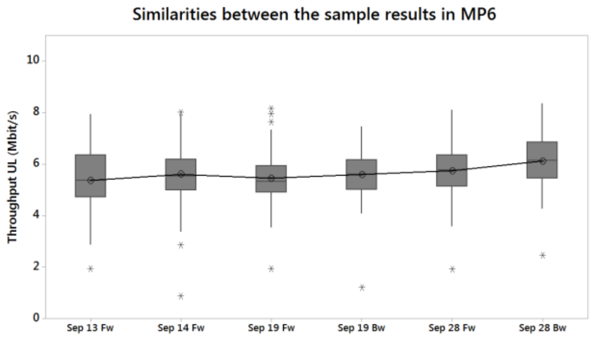

Fig. 9. MP 6 measurements back and forth with H2 configuration.

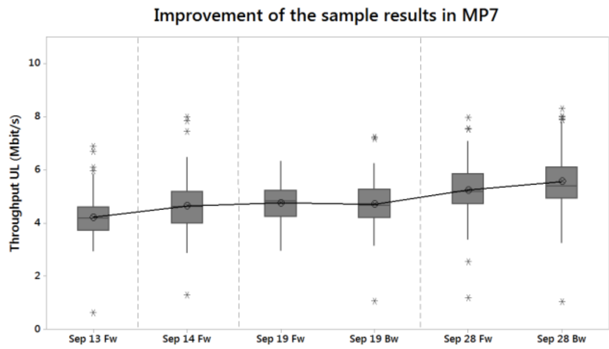

Fig. 10. MP 7 MAC throughput increase during September with H2 configuration.

September, the average throughput was 4.23 Mbit/s, and in late September, the throughput was 5.57 Mbit/s. The throughput increase was approximately 32%. The statistical significance of the throughput increase was studied with 2-sample t –test. Since the measurement sample sizes were around 100 samples per measurement we examined the -0,30 Mbit/s difference with uncertainty level p of 0.10. The results of tests are given in Table VI. Table VI reveals that the throughput of the first measurement day of September 13 is statistically significantly lower than the throughput of any

TABLE VI.
RESULTS OF 2-SAMPLE t TEST FOR THROUGHPUT (*TP*) MEAN AT MP7

Hypothesis	**Significantly true**	**Diffrence (Mbit/s)**	***p***
$\overline{C}_{\text{Sep 13 Fw}} < \overline{C}_{\text{Sep 14 Fw}}$	Yes	-0.42	< 0.001
$\overline{C}_{\text{Sep 13 Fw}} < \overline{C}_{\text{Sep 19 Fw}}$	Yes	-0,53	< 0.001
$\overline{C}_{\text{Sep 13 Fw}} < \overline{C}_{\text{Sep 19 Bw}}$	Yes	-0,48	< 0.001
$\overline{C}_{\text{Sep 13 Fw}} < \overline{C}_{\text{Sep 28 Fw}}$	Yes	-1,01	< 0.001
$\overline{C}_{\text{Sep 13 Fw}} < \overline{C}_{\text{Sep 28 Bw}}$	Yes	-1,34	< 0.001
$\overline{C}_{\text{Sep 14 Fw}} < \overline{C}_{\text{Sep 19 Fw}}$	No	-0,11	0.140
$\overline{C}_{\text{Sep 14 Fw}} < \overline{C}_{\text{Sep 19 Bw}}$	No	-0,06	0.282
$\overline{C}_{\text{Sep 14 Fw}} < \overline{C}_{\text{Sep 28 Fw}}$	Yes	-0,59	< 0.001
$\overline{C}_{\text{Sep 14 Fw}} < \overline{C}_{\text{Sep 28 Bw}}$	Yes	-0.92	< 0.001
$\overline{C}_{\text{Sep 19 Fw}} < \overline{C}_{\text{Sep 28 Fw}}$	Yes	-0,48	< 0.001
$\overline{C}_{\text{Sep 19 Fw}} < \overline{C}_{\text{Sep 28 Bw}}$	Yes	-0,81	< 0.001
$\overline{C}_{\text{Sep 19 Bw}} < \overline{C}_{\text{Sep 28 Fw}}$	Yes	-0,53	< 0.001
$\overline{C}_{\text{Sep 19 Bw}} < \overline{C}_{\text{Sep 28 Bw}}$	Yes	-0,86	< 0.001

subsequent measurement days. Similarly, the throughput values at September 28 are statistically significantly higher than the throughput of any previous measurement days. There is a slight increase in throughput on September 19 versus the throughput on September 14 even though this increase is not statistically significant. The found increase of throughput in some MP results can be explained via the environmental foliage decreased during late autumn. This effect is expected as many studies have reported the decrease of the attenuation of trees without foliage e.g. [14-16].

A. NLOS Comparison

By comparing the different measurement points handling different antenna configurations in Table V, one can identify which NLOS points achieved the best throughput values. All throughput values in Table V are average values of the results. When the beam was steered towards UE, MP 4 had a -34° azimuth and MP 5 had a -17° azimuth angle. MP 6 and MP 7 were virtually in the same direction as azimuth 0°; therefore, the azimuth angle was not changed for the MP 6 and MP 7 locations. MP 4 had the best throughput performance with the H2 steering configuration. The throughput was 8.57 Mbit/s. MP 5, MP 6, and MP 7 reached the best throughput performance with the V4 configuration. The throughput for MP 5 was 7.32 Mbit/s, for MP 6 it was 6.60 Mbit/s, and for MP 7 it was 6.08 Mbit/s.

During the analysis phase, it was noticed that there was no single configuration feature that would produce the best throughput for all measurement points.

B. Throughput Gain Comparison

Throughput gain comparison was performed for points MP 4 to M P7 by comparing different configurations used for these points. In order to evaluate the improvement of the performance the Throughput Gain (TG) for each antenna configuration was calculated according to the following formula:

$$TG[\%] = 100\left(\frac{C_1 - C_2}{C_2}\right) \quad (1)$$

Wherein C_1 [Mbit/s] is the throughput of the first configuration and C_2 [Mbit/s] is the throughput of the second configuration. The results are reported in Table VII. When comparing the different configurations in Table VII with each other, one can see which antenna configuration had the most percentage throughput gain. Measurement gain values were gathered by comparing the throughput data with each measurement setup. At each selected measurement point, the two-column passive configuration measurements were better when comparing the values with the single-column passive configuration. The throughput gain values varied in this comparison from 35% to 48%, depending on the measurement point. When comparing the single-column AAS with the single-column passive configuration, the measurements indicated that all single-column AAS measurements had better throughput gain results. In this situation, the throughput gain varied from 47% to 87%, depending on the measurement point. When comparing the single-column AAS with the two-column passive configuration, the throughput gain results indicate that for most measurement points, there were positive throughput gain values, especially for MP 5 and MP 6. The throughput gain varied from 7% to 27%, depending on the measurement point. The throughput gain results are positive for measurement points when comparing the four-column AAS beam steering with the single-column passive configuration. The throughput gain results varied in this comparison from 25% to 78%. In four-column AAS steering, the azimuth angle for MP 4 was -34°, and for MP 5, it was -17°. For the four-column AAS steering and the two-column passive throughput gain comparison, the results were mostly positive; only MP 7 produced negative throughput gain. The throughput gain results varied in this comparison from -12% to 20%. When comparing the four-column AAS steering with the single-column AAS configuration, positive throughput gain results were measured from MP 4, and the rest of the measurement points produced negative throughput gain results. The results varied in this comparison from -20% to 6%.

TABLE VII.
PERCENTAGE GAIN VALUES

Compared configurations	Gain[%] measurements			
	Min	Max	Avg.	St. Dev.
P4 vs P2	34.56%	47.57%	40.46%	5.72%
V4 vs P2	47.19%	87.21%	63.02%	17.21%
H2 steering vs P2	24.87%	77.49%	49.10%	22.71%
V4 vs P4	7.13%	26.86%	15.94%	9.24%
H2 steering vs P4	-12.25%	20.28%	6.04%	14.12%
H2 steering vs V4	-19.90%	5.67%	-8.45%	11.20%

VIII. Discussion and Conclusion

This article describes the test method development for dynamic cellular network and uplink throughput gain evaluation in field trials. The field trial described in this article evaluated uplink throughput gain in a non-line-of-sight environment while using passive, 2-way and 4-way RX diversity in horizontal and vertical beamforming in a suburban/rural area of Ylivieska, Finland. The study, with statistical analyses, clearly revealed that measurements in a challenging radio propagation environment with moving UE produced more reliable and repeatable results than measurements with stationary located UE. From the throughput gain results, it was concluded that there is no single configuration feature that will provide the best throughput for all measurement points. The vertical AAS was shown to deliver a throughput gain up to 87.21% in the uplink direction, while the horizontal beam steering was shown to deliver a throughput gain up to 77.49% in the uplink direction. The best configuration for MP 4 was the four-column AAS steering, but the single-column AAS was almost as good as four-column AAS steering. In MP 5, MP 6, and MP 7, the AAS configuration with single-column 4-way RX diversity produced the best measurement results. The UE-specific beamforming feature can have effects on signaling and additional information exchanges, for example, when the eNB must estimate the location of the UE or the UE must inform which beams are best for transmission. However, in this beam steering measurement setup, there was no need for any additional signaling or information exchange, because the UE was in static locations, and the UL beam was steered manually towards the selected measurement points. The use of different elevation beams with the RX diversity feature made it possible to achieve useful gain signals for selected measurement points. This combination can also utilize separate MIMO streams in the future. This study produced promising results for network performance improvements when vertical and horizontal beamforming are used in a challenging non-line-of-sight environment. The vertical AAS produced the most promising values, at least in these tests and in this test environment setup. Horizontal beamforming is useful when the beam is steered towards the user. While this study concentrated on evaluating uplink throughput gain in a challenging non-line-of-sight environment, previous study results [23] indicate that AAS with vertical sectorization can offer an 84.6% gain in downlink throughput. The research results that have been produced thus far indicate that different NLOS locations have different multipath profiles in horizontal and vertical dimensions. Parallel placement of two antennas at the Puuhkala site might have slightly affected the measurements done on the sector borders, which is why a wider study is to be conducted for future 5G test measurements.

Changes in next-generation mobile networks have created a need to further develop field test methods, particularly to evaluate the performance of future dynamic mobile networks. The potential of unmanned aircraft systems will be researched in future trials to meet the challenges of testing mobile networks with 3D beamforming of AAS.

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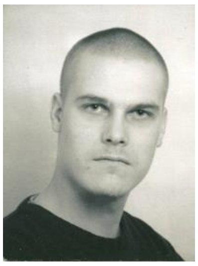

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