Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2021) 29: 276 – 290
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doi:10.3906/elk-1912-81

Real-time measurements and performance analysis of closed-loop MIMO service for mobile operators

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Received: 13.12.2019 • **Accepted/Published Online:** 10.08.2020 • **Final Version:** 27.01.2021

Abstract: As fifth generation (5G) networks are starting to become commercial, user expectations in terms of new services become high as well. This signifies that mobile communications service providers need to build robust 5G new services as quickly and cost-efficiently as possible. Many new technologies rely on closed-loop (CL) and multiple input multiple output (MIMO) technologies due to emerging cooperation between nodes in next generation networks. In this paper, we first compare different multiantenna transmission modes namely: transmit diversity, open-loop (OL), and CL MIMO spatial multiplexing strategies to provide mobile network operator (MNO) services in terms of their characteristics, ,limitations and benefits. Later we investigate how launching a large-scale CL MIMO deployment strategy can affect the various key performance indicators (KPIs) of the existing services provided by Mobile Network Operators (MNOs) in real-operational network infrastructure in Turkey. Our practical experimental results indicate that, compared to OL MIMO system, CL MIMO can achieve large performance on a practical setup, where up to 3% improvement in cell average throughput, 9% in user throughput, 6% in spectrum efficiency, and 9% in channel quality indicator (CQI) and modulation coding scheme (MCS) are obtained, while reduction by 25% and 17% on sum delay and initial block error rates (IBLER) are observed.

Key words: Closed-loop, multiple input multiple output measurements, real-time testbed

1. Introduction

The Fifth Generation (5G) networks are expected to provide low latency, massive connectivity, and high throughput to diverse set of applications and devices. One of the important features of 5G networks will be to support various subscriber services [1]. Techniques such as Multiple-input multiple-output (MIMO) provide significant increase on the effectiveness of the mobile transmission that reduces the radio interference across the cell. Thus, better user experience for MNOs services can be achieved as a result. Millimeter-wave (mmWave) based 5G service can be affected by the surrounding environment, such as building shadowing, reflection, rain attenuation, etc. This delay and noise sensitivity would make providing feedback on Closed-Loop (CL) systems more critical in terms of their coverage enhancement abilities. The primary requirement to enable CL systems is the capability of end-user devices to support the system. Mobile communication systems allow the usage of channel information to implement CL techniques between user equipment (UE) and Base Station (BS). The information in this channel can be utilized to increase the system's effectiveness without a requirement

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of complex receiver architecture. Moreover, lossless and reliable data transmission with CL systems is also important for some next generation services that are mission-critical and cannot tolerate a single packet loss.

MIMO systems contain multiple antennas to improve the connectivity of UEs. To run MIMO algorithms effectively, a significant coordination support is required between BSs and UEs. In order to utilize all the capabilities of MIMO technology, two types of mechanisms are defined in long term evolution (LTE)-advanced and 5G. These are Open-Loop (OL) and CL MIMO schemes. OL MIMO has been used in the literature in combination with different schemes such as Downlink (DL) multi-user Sparse Code Multiple Access (SCMA) (MU-SCMA) or coordinated multi-point (CoMP) transmission for Ultra Dense Network (UDN) [2]. In time and frequency response of the spatial channel, there are variations that affect the performance of the channel. CL MIMO method leverage the channel feedback information to track these variations accurately [3]. CL MIMO systems are under the focus of industry for 5G communications. 5G New Radio (NR) data transmission is expected to utilize CL MIMO dynamic pre-coding scheme as one way to improve the spectral efficiency [4]. 5G Stand Alone (SA) [5] beam management technique requires CL MIMO system to determine the *best* beam from the UE point of view. CL MIMO solution operates in a dynamic manner, since the mobility of the UE changes in the coverage area. For this reason, it is essential to investigate the performance gains of CL MIMO solution in pre-5G deployments.

2. Related work and motivation

In the literature, many studies on the enhancements and the performance gains for CL and OL based MIMO systems exist. CL and OL based single user MIMO solutions have been studied in combination with Non-Orthogonal Multiple Access (NOMA) in [6]. Closed loop spatial multiplexing (CLSM) scheme is envisioned to be utilized in various 5G applications including UDNs, massive MIMO, and mmWave (and/or terahertz)-based BSs [7]. In [8], a general expression for the probability density function is proposed to derive the system Bit Error Rate (BER) and ergodic capacity in CL for MIMO systems with performance results where it has been shown that ideal CL MIMO provides a 2 dB theoretical performance link gain corresponding to 20% higher spectrum efficiency over OL MIMO. The article in [9] examined the effect of the transmit antenna correlation on the CL throughput of a 2×2 CL MIMO system. Potential learning schemes to achieve and exceed performance of existing MIMO schemes and their performance evaluations using both OL and CL operations in MIMO systems are presented in [10]. The paper in [11] provides a detailed performance comparison between CL and OL MIMO schemes based on system level simulation results and show 2 dB link gain (corresponding to 20% spectral efficiency) theoretical improvements in ideal conditions and 1 dB (corresponding to 10% capacity gain in fully loaded network scenario) when practical constraints are considered. In [12], the impact of different cellular network deployments, antenna configurations, and transmission schemes on achievable performance are examined through theoretical and simulation studies for multiantenna heterogeneous networks (HetNets). System-level simulations are conducted in [13] with the specified aspects mostly affect the capacity and spectrum efficiency of LTE network which also includes CL MIMO. CL MIMO is shown to provide valuable signal-to-interference-plus-noise ratio (SINR) gains compared to OL MIMO via simulations even under Channel Status Information (CSI) feedback error scenarios in [14]. However both of these approaches ([13, 14]) are based on system level simulations that lack experimentation with real-world operational environments inside a MNO infrastructure.

There are also system-level studies for MIMO in the literature. A system level analysis on user-centric scheduling for a flexible 5G radio design with using CL MIMO is presented in [15]. OL and CL training systems are proposed in [16] as a framework that is using successive channel prediction/estimation at the user for Frequency Division Duplexing (FDD). Relationship between beam-forming and MIMO techniques is investigated in [17]. The authors in [18] design a precoding matrix using wider beamwidths in both CL and OL MIMO transmission schemes to enhance the throughput values for 5G new radio (NR) systems. An iterative algorithm based on an alternating minimization procedure using interference alignment for MIMO is proposed in [19]. A method that dynamically configures the transmission parameters for multiple MIMO streams is proposed in [20]. CL MIMO system is extended for 5G networks in patent [21] so that each receiver is adapted to transmit at least one type of feedback information selected from a antenna selection group. Another CL MIMO system patent in [22] is proposing variations on the feedback information, so the payload may be configured to 6 bits including a Precoding Matrix Index (PMI) or 4 bits representing a PMI and 2 bits representing a differential SINR. A detailed comparison of CL and OL MIMO in LTE is given in [11]; however, the analysis results are based on system level simulations. The patent in [23] is proposing a method for dynamic switching between CL and OL MIMO for multistream processing. The authors in [24] investigate the experimental performances of vehicular throughput of different transmission modes (TMs) (including transmit diversity, OL, and CL spatial multiplexing transmission) in different carrier frequencies and MIMO configurations modes. The authors report that TM-2 mode is shown to be utilized mostly due to its robustness against mobility and poor channel conditions during field measurements of a residential district in İstanbul, Turkey. The paper in [25] investigates the BER performances of CL and OL MIMO schemes using Minimum Mean Squared Error (MMSE) and Zero Forcing (ZF) equalizers. They report the involved trade-offs of using different equalizers under different TMs, but they used LTE-advanced link level MATLAB simulator (MathWorks, Inc., Natick, MA, USA). The authors in [26] have derived capacity expressions in terms of the maximum to minimum singular value ratio for both OL and CL MIMO schemes.

In this paper, approaches different than the ones mentioned above (which are either focusing on simulation based studies or non-practical settings for experimenting with CL MIMO solution), we investigate the MIMO systems in the perspective of a service that is provided by MNOs in a real deployment scenario. While theoretical structure and possible enhancements of MIMO CL and CL techniques have been studied extensively in literature, there is little information on the service level implementation of MIMO techniques for MNOs using large-scale deployments. Therefore, our efforts concentrate on addressing the real-world implementation of CL MIMO feature in an operational telecommunication infrastructure and observing its effect on large-scale deployment scenarios. CL MIMO implementations have been covered in academic literature but little information is available for the CL MIMO systems in practical systems when it is provided as a service to MNO users. To show the benefits of CL MIMO in real-world operational networks, we compare its performance with OL MIMO by observing different Key Performance Indicators (KPIs) that are used within MNOs. Main contributions of this paper can be summarized as follows:

- We use real-telecommunication operator's infrastructure to fully exploit the benefits of CL MIMO in large-scale deployment scenarios.

- We provide insights on the benefits and limitations of open and CL MIMO implementation scenarios and evaluate their impact on different observed KPIs of evolved Node-B (eNodeB) for a total of three months in operational network sites in Turkey.

- Our experimental results indicate that CL MIMO yields improvements on many KPIs (i.e. 6% increase in spectrum efficiency, 9% in user and 3% in cell throughput, higher modulation usage by 27% increase in 64 Quadrature amplitude modulation (QAM) utilization, 9% in both Channel Quality Indicator (CQI) and Modulation Coding Scheme (MCS), 25% reduced delay and 17% reduced Initial Block Error Rate (IBLER)) compared to OL MIMO on different cities of Turkey.

The rest of the paper is organized as follows: Section 3 presents the system model and concepts related to different MIMO deployment strategies as well as comparisons of OL and CL MIMO strategies to provide MNO services. The experimental results are presented in Section 4 as well as provides discussions on main takeaways issues that need to be considered. Finally, in Section 5, we provide the conclusions and future work of the paper.

3. System model and concepts

We assume that there are K_l UEs with N transmit and receive antennas in each cell $l \in \mathcal{L}$ with where $\mathcal{L} = \{1, 2, \dots, L\}$ is the set of cells and L is the total number of cells in the considered geographic region. The channel between UE-k in cell l is denoted by $\mathbf{h}^l_{l,k}$ which is a $N \times 1$ vector. In OL MIMO transmission scheme (e.g. in LTE TM-3 mode), the received DL signal $y_{l,k} \in \mathcal{C}$ at UE-k in cell l is given by

$$y_{l,k} = (\mathbf{h}^j_{l,k})^H s_{l,k} + \sum_{m=1}^{L} \sum_{\substack{i=1 \\ (m,i)\neq(l,k)}}^{K_l} (\mathbf{h}^l_{m,i})^H s_{m,i} + n_{l,k} \tag{1}$$

,

where BS l transmits the signal $\mathbf{x}_l = \sum_{i=1}^{K_l} s_{l,i}$ and receiver noise $n_{l,k} = \mathcal{N}_{\mathcal{C}}(0, \sigma^2)$. The received SINR at user $k \in \mathcal{K}_l$ is

$$SINR_{l,k} = \frac{|\mathbf{h}^j_{l,k}|^2 P_{l,k}}{\sum_{m=1}^{L} \sum_{\substack{i=1 \\ (m,i)\neq(l,k)}}^{K_l} P_{m,i} |\mathbf{h}^j_{m,i}|^2 + \sigma^2} \tag{2}$$

,

where $P_{k,l}$ is the transmitted power from BS $l \in \mathcal{L}$ to UE-k. In CL MIMO transmission scheme (e.g. in LTE TM-4 mode), the received DL signal $y_{l,k} \in \mathcal{C}$ at UE-k in cell j is given by

$$y_{l,k} = (\mathbf{h}^j_{l,k})^H \mathbf{w}_{l,k} s_{l,k} + \sum_{m=1}^{L} \sum_{\substack{i=1 \\ (m,i)\neq(l,k)}}^{K_l} (\mathbf{h}^l_{m,k})^H \mathbf{w}_{m,i} s_{m,i} + n_{l,k} \tag{3}$$

,

where BS l transmits the signal $\mathbf{x}_l = \sum_{i=1}^{K_l} \mathbf{w}_{l,i} s_{l,i}$ and pre-coding vectors $\mathbf{w}_{l,k} \in \mathcal{C}^{M_l}$ satisfy $\mathcal{E}\{||\mathbf{w}_{l,k}||^2\} = 1$. The received SINR at user $k \in \mathcal{K}_l$ is

$$SINR_{l,k} = \frac{|(\mathbf{w}^j_{l,k})^H \mathbf{h}^j_{l,k}|^2 P_{l,k}}{\sum_{m=1}^{L} \sum_{\substack{i=1 \\ (m,i)\neq(l,k)}}^{K_l} P_{m,i} |(\mathbf{w}^j_{m,i})^H \mathbf{h}^j_{m,i}|^2 + \sigma^2} \tag{4}$$

,

where $\mathbf{w}_{m,i}^{j}$ is the pre-coding vector to cancel the interference at cell l for UE-k. The throughput of a cellular network in a given area which is measured in bps/km^2 can be be calculated as

$$T = B[Mhz] \times D[cells/km^2] \times SE[bps/Hz/cell] \tag{5}$$

, where B is the bandwidth, D is the average cell density, and SE is the per-cell Spectral Efficiency (SE) which represents the amount of information transferred per second over a unit bandwidth [27]. In practical BS deployments, when BS receives the SINR values, it first maps it into CQI and later into spectral efficiency using 3GPP specification tables (see Table 7.2.3-1 in [28]). Finally it loops through MCS indexes to find the best Transport Block Size (TBS)- MCS pair that can approximate the obtained spectral efficiency and maps an MCS index into a TBS (see Table 7.1.7.1-1 in [28]) during one Transmission Time Interval (TTI).

3GPP specification has also worked on defining propagation models for urban channels. For urban areas which of interest in our experiments, 3GPP has defined macro-cell propagation model [29]:

$$L = 40 \times (1 - 4 \times 10^{-3} \times Dhb) \times log_{10}(R) - 18 \times log_{10}(Dhb) + 21 \times log_{10}(f) + 80dB \tag{6}$$

, where R is the base station-UE separation in kilometres, f is the carrier frequency in MHz, Dhb is the base station antenna height in metres, measured from the average rooftop level. The UE transmit power $P_{l,k}$ from UE-k to BS $l \in \mathcal{L}$ is

$$P_{l,k} = P_{max} \times min\left(1, max\left(R_{min}, \left(\frac{CL}{CL_{x-idle}}\right)^{\gamma}\right)\right) \tag{7}$$

, where P_{max} is the UE maximum transmit power, R_{min} is the minimum power reduction ratio to prevent UEs with good channels to transmit at very low power level, CL is the path coupling loss defined as max{path loss-G_{Tx}-G_{Rx}, MCL}, where path loss is propagation loss plus shadowfading, G_{Tx} is the transmitter antenna gain in the direction of the receiver, G_{Rx} is the receiver antenna gain in the direction of the transmitter, MCL is minimum coupling loss (selected to be 70 dB in macro cell urban areas), $0< \gamma <1$ is the balancing factor for UEs with bad channel and UEs with good channel, and CL_{x-ile} is the x-percentile CL value. [29].

Figure 1 shows the operation of MIMO schemes with different classes of UEs. Figure 1a shows OL MIMO scheme where UEs are reporting CQI and Rank Indicator (RI) values whereas Figure 1b shows CL MIMO scheme, where UEs reports CQI, RI and PMI values. RI is used to indicate the number of MIMO layers, PMI is used for beamforming operation at BS for each layer and CQI is used to obtain the required MCS index value. MIMO works at its best performance if one of the antennas doesn't make interference on to the other antenna. In MIMO, RI value is very closely related to the number of antennas. In the case of 2 x 2 MIMO, RI value may be 1 or 2. If the two antennas do not create interference on each other, then the RI value is set to 2, otherwise RI value is set to 1. RI values supported by UEs vary according to LTE TM classes [29] of UEs. TM3 or 4 UEs support RI 1 and 2. TM2 UEs do not support RI value 2 and operate at RI value 1. If the RI is 2, the UE is able to communicate with two different data streams that have direct affect on the throughput increase. In UEs with a RI value of 1, the same data streams flow over different antennas. In this case, the throughput is expected to be less, while the data loss due to radio conditions is also expected to be less. TM3 and TM4 MIMO provide higher peak throughput when using rank 2 that allows two code words on two antennas with spatial multiplexing.

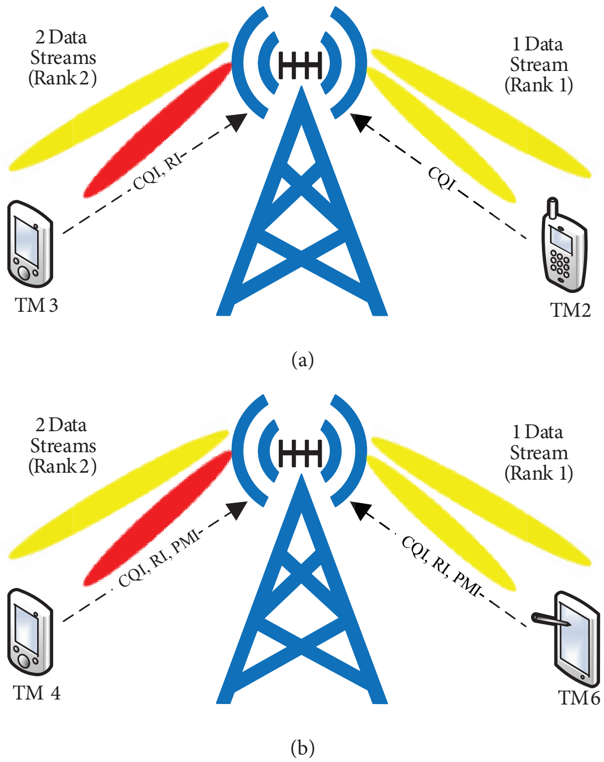

Figure 1. Operation of MIMO schemes with different classes of UEs (a) Open-loop MIMO, UEs reporting CQI and RI (b) Closed-Loop MIMO, UEs reporting CQI, RI and PMI.

Table 1 provides the comparisons of MIMO strategies, namely OL transmit diversity, OL, and CL MIMO spatial multiplexing strategies that are experimented in this paper to provide MNO services. OL MIMO schemes are intended for cases when no partial CSI information is available at BSs. In OL MIMO, UE reports only CQI and RI values as CSI. OL MIMO needs low feedback overhead and is more robust against CSI errors. This in turn results in low system complexity. Moreover, OL MIMO is more suitable for high mobility cases. On the other hand, OL MIMO has its own limitations as well. Some of its limitations are as follows: signal matrix is designed irrespective of the channel, UE rotates between all available PMIs and inaccurate PMI selection can decrease capacity gains. On the other hand, OL MIMO exploits both Cyclic Delay Diversity (CDD) and transmit diversity.

At run time, CL MIMO uses accurate channel feedback as an indispensable requirement. CSI in CL MIMO includes CQI, RI and PMI. Feedback information from the UE supports eNodeB to perform link adaptation and beamforming. RI and CQI indicate recommended number of data streams and data rate per stream, respectively. Different than OL MIMO, the PMI in CL MIMO is also reported by UE to the eNodeB so that it can use more suitable codebook for precoding purposes. This can enhance the performance in DL. The feedback method used in CL MIMO can work in both FDD and Time Division Duplexing (TDD). The UE needs to report CSI which is an indicator how good or bad the channel is at a specific time. Based on these reports, eNodeB determines the *transport block* sizes to send the data, which in turn can be directly converted into throughput. PMI is used to combine the two signals transmitted by the two antennas of eNodeB. The PMI value is measured and reported by UE. This UE based PMI determination method is more suitable for UEs than the one that is

Table 1. Comparisons of multi antenna transmission modes: OL transmit diversity, OL, and CL MIMO spatial multiplexing strategies to provide MNO services.

MIMO Strategy	Characteristics	Limitations	Advantages/ Benefits
Transmit diversity strategy	— UE reports only CQI. — Uses space-frequency block code in the frequency domain. — Transmit one codeword on each antennas (rank 1 transmission).	— Not efficient at high SINRs — Does not enhance the transmission data rate. — Not multistream transmission (due to rank loss).	— Provides better coverage and throughput for cell-edge users — Best suited transmission multiantenna scheme at low SINR. — Robust transmission against channel impairments and mobility.
Open loop strategy	— UE reports CQI and RI. — Does not require any knowledge about the channel at the transmitter. — Transmission on one or two codewords (rank 1 or 2 transmission).	— Signal matrix is designed independent from the channel. — UE rotates between all available PMIs. — Inaccurate PMI selection brings less capacity gains. — Suffers from power imbalances over multiple streams and high channel correlations.	— Low feedback overhead. — Robust against CSI errors. — Low system complexity. — Best for high mobility cases. — Does not bring extra delay with reporting & processing. — Spatial multiplexing can enhance the transmission data rate at high SINR. — Utilizes CDD as well.
Closed loop strategy	— UE reports CQI, RI and PMI. — Takes time for UE to send the report and for BS to process it. — The decision after the reception of the report will only be applicable in next transmission. — Transmission on one or two codewords (rank 1 or 2 transmission).	— Requires accurate channel feedback (to keep channel orthogonality). — Cross-layer interference in case CSI is not estimated well. — Practical difficulties (e.g. channel aging, estimation impairments brings high overhead to UEs). — High challenges in case coordination is required (e.g. in CoMP scenarios). — Small transmission bursts can drain the UE battery (due to frequent CSI feedbacks).	— Selects best PMI. — Provides more coverage and throughput. — Suitable for indoor locations. — Effective in conditions where channel is less time-variant. — Great benefit for noncritical services. — Better performance for slow-moving UEs. — Spatial multiplexing can enhance the transmission data rate at high SINR.

chosen by eNodeB in the OL MIMO. So, UE with CL MIMO could receive more powerful signal from eNodeB (array gain) which will improve CQI and in turn improve DL cell and user throughput. PMI is the recommended index indicating the preferred pre-coding matrix. PMI information is reported from the UE traffic to indicate the preferred set of weights to be applied during the precoding process. The UE does this to maximize the link SINR rate by providing feedback. CL MIMO is more efficient than OL MIMO in low mobility environments where user's radio conditions do not change rapidly. CL MIMO is expected to provide better results in indoor scenarios where the mobility of UEs is low and can be beneficial for noncritical services. Obtaining reliable CSI is critical for the operation of CL techniques. Some of CL MIMO's limitations are domination of cross-layer interference when CSI is not estimated well, practical difficulties such as channel aging, estimation impairments brings high overhead to UEs that may exist. Moreover, in case coordination is required either between cells or cells and UEs (e.g in CoMP [30] or Single Frequency Network (SFN) [31] scenarios) the challenges increase. In the MNO environment, each eNodeB can be configured separately as OL and CL. However in SFN case, since eNodeBs constitute a single cell, only OL or CL can be selected which eliminates different MIMO configuration flexibility for each eNodeB.

Both CL and OL MIMO spatial multiplexing schemes support rank 1 and rank 2 transmissions. In case where rank 1 is used, both schemes become similar to transmit diversity. In rank 2 transmission, codewords are transmitted on multiple antennas by using spatial multiplexing. Under certain conditions (e.g at high SINR), spatial multiplexing can enhance the transmission data rate. During practical operation, first initial *random access (RA)* transmit diversity is used towards UEs. After the reception of *Radio Resource Control (RRC) connection setup* message by UEs, OL or CL MIMO with spatial multiplexing is used. The transmission scheme and correspondingly the CSI content is adjusted using *RRC* signaling.

4. Experimental results

We performed experiments for monitoring and comparing CL and OL MIMO between 02 August 2018 and 31 October 2018 (i.e. for 3 months). During experiments, observation duration during which OL MIMO was activated was between August and September 2018, whereas CL MIMO was activated in October 2018. The experiments were run in 6 major cities (İstanbul, İzmir, Antalya, Bursa, Kocaeli, and Adana) of Turkey that are located in different geographic regions and KPIs are averaged over all the considered locations.

All 3GPP compliant parameters that are used in experiments for CL and OL MIMO schemes are summarized in Table 2. For configuring frequency bands, LTE specific parameters such as carrier frequency, bandwidth, modulation types, etc. are used. Carrier frequency is 800 Mhz (for 10 Mhz bandwidth) or 1800 Mhz (for 20 Mhz bandwidth) and modulation types are QPSK, 16 QAM and 64 QAM. The experiment parameters and the scenarios in our experimental study match with the specifications proposed by The 3rd Generation Partnership Project (3GPP). All the experiments were done in urban areas which corresponds to urban macro model in [29]. The system scenario is set for the FDD system parameters and FDD coexistence scenario as specified in [29]. The selected experiment models and the experiment configurations of carriers for transmitters are configured as defined in [32].

Figure 2 shows the DL spectrum efficiency values for both OL and CL MIMO in bits/Hz/sec over the observation duration. Spectrum efficiency measures the bits per Physical Resource Block (PRB) in Hz and is calculated as DL cell throughput in bits divided by number of PRBs used by Physical Uplink Shared Channel (PUSCH) dedicated radio bearer per msec, Resource Block (RB) in Hz and number of DL antennas. We can

Table 2. Parameters used during experimental setup.

Parameter	Value	Parameter	Value	Parameter	Value
Total number of eNodeBs (with CL MIMO)	~ 500	# of cells per eNB	3	PDSCH power (avg)	45.8 (dBm)
PDCCH power (avg)	45.4 (dBm)	eNB Antenna gain	17.32 dBi	Antenna pattern	X polarization
eNodeB Max. power	46 dBm	Min. RSRP (Reference signals received power	-130 dBm	Antenna configuration	2 x 2
LTE duplex mode	FDD	Inter-cell distance (avg.)	305.63 m	System bandwidth	10 & 20 MHz
eNodeB noise figure	5 dB	Carrier frequencies	800 & 1800 MHz	—	—

observe that CL MIMO can provide up to 6% improvements compared to OL MIMO where the average value increased from 1.37 to 1.44 bits/Hz/sec. Figure 3 shows percentage usage of different modulation schemes where 64 QAM usage percentage has increased 27% and QAM and 16 QAM percentage usage have decreased 17% and 5% respectively. These results clearly demonstrate that together with CL MIMO, percentage of higher order modulation utilization has increased.

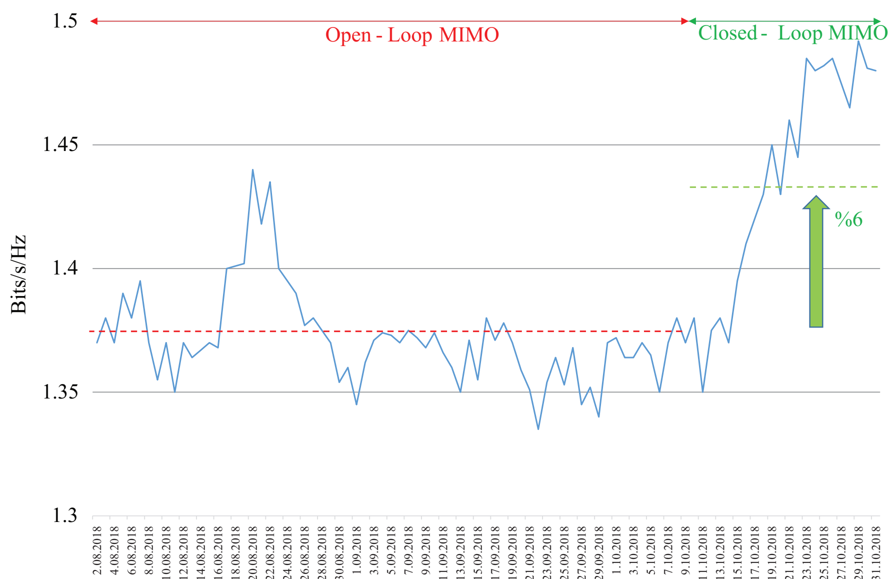

Figure 2. Comparison of downlink spectrum efficiency of open-loop and closed-loop MIMO.

Figure 4 shows average user and cell throughput values for both OL and CL MIMO systems. Cell throughput measures the cell capacity. User DL throughput has increased 9% and cell DL throughput has increased 3% after activation of CL MIMO feature in the considered sites. Figure 5 demonstrates the variations of average CQI and MCS index values in DL direction. Compared to OL MIMO scheme, average CQI and MCS values have increased 9% together with the introduction of CL MIMO in the considered sites.

Figure 6 shows the comparisons of the sum of DL packet delay and DL IBLER values for OL and CL MIMO schemes covering all UEs. Together with CL MIMO, it is observed that sum of DL packet delay and DL IBLER values have decreased by 25% and 17%, respectively. These results indicate the importance of application of CL MIMO for deployment of critical-services that require low latency and high reliability.

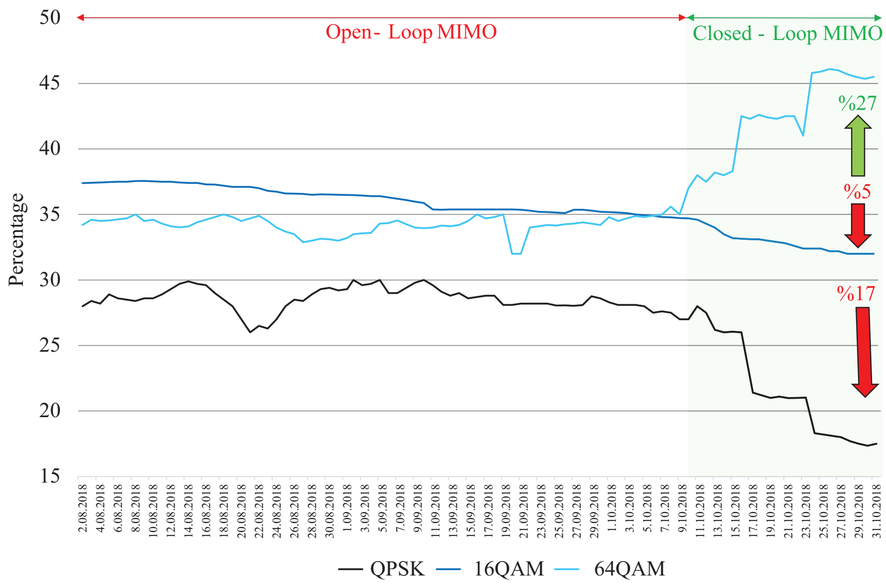

Figure 3. Modulation usability (%) KPI obtained from the real-time testbed.

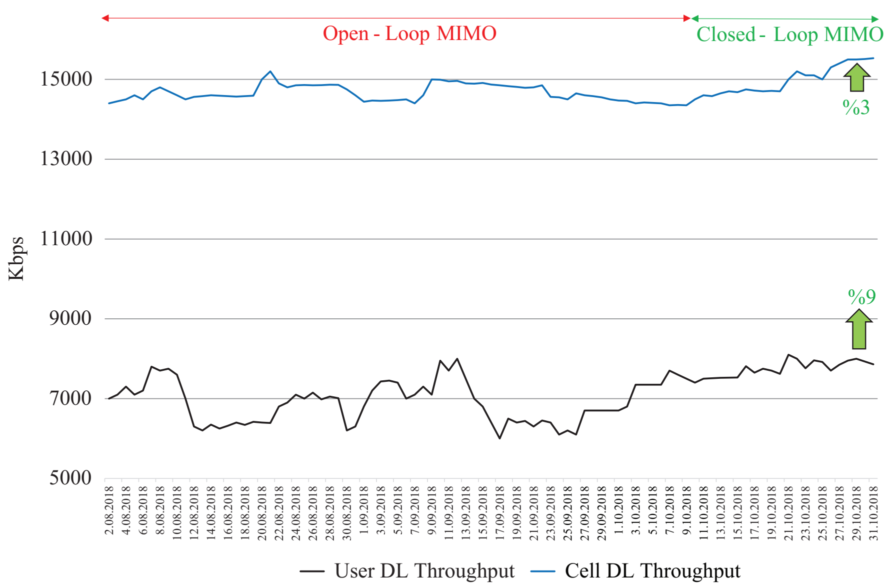

Figure 4. User and cell downlink throughput KPI obtained from the real-time testbed.

Finally, Figure 7 shows the overall KPI improvements after CL MIMO is activated in different cities of Turkey. We can observe obtained gains in terms of DL user and cell throughput, spectrum efficiency, CQI values, and modulation usability increase in 64 QAM and 16 QAM in different locations of Turkey. The highest increase has been on the usage of 64 QAM, whereas the lowest percentage gains are on cell DL throughput values. On the other hand, QAM usage by BSs has been reduced dramatically by around 40% in all cities. Figure 7 shows that depending on the CQI increments, the highest user DL throughput was experienced in Antalya. The reason for this situation can be explained by the fact that the experimental feature test was

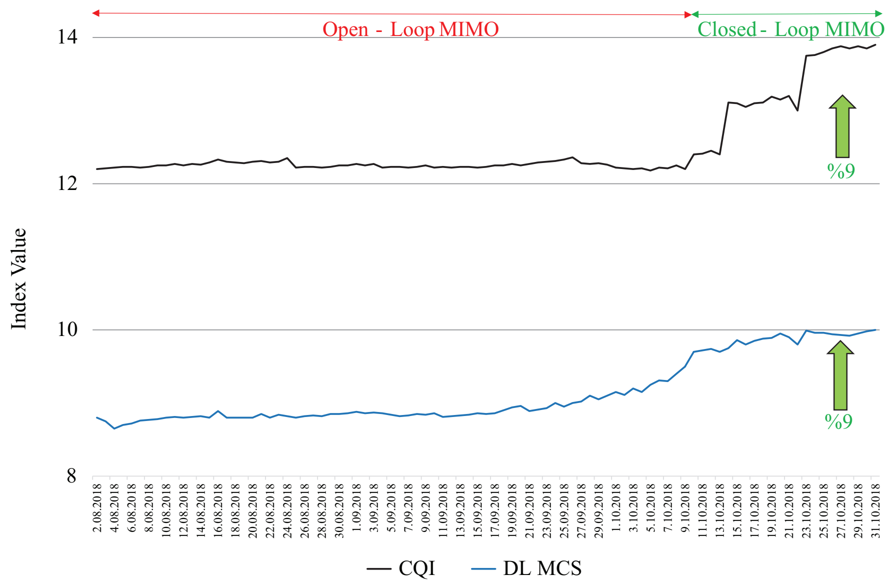

Figure 5. Average CQI and average downlink MCS KPI obtained from the real-time testbed.

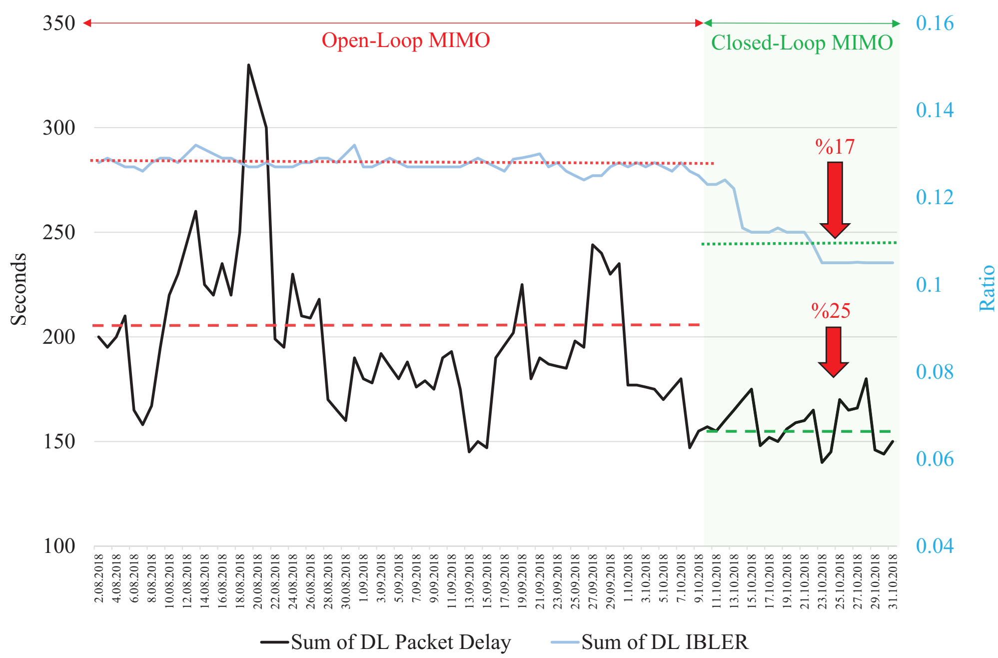

Figure 6. Comparison of sum of delay and IBLER between open-loop and closed-loop MIMO.

carried out in the summer months, (i.e. in good weather conditions corresponding to higher number of UEs benefiting from CL MIMO feature activation) and low UE mobility ratios due to the fact that Antalya being a touristic destination city. City of Izmir is the location which exhibits the lowest increment among all other cities. This the due to the low number of UE ratios with CL MIMO support. There is small increment in the number of UEs using 64 QAM in the city of Kocaeli as well. In parallel, there is no major increase in MCS index and CQI values whereas high user DL throughput values have been observed in the city of Kocaeli. This is due to the existence of high number of UEs per cell (i.e. existence of high density cells), which results in high throughput values even when small increments in MCS index and CQI values occur. In cities of Bursa and Adana, the use of 64 QAM and the average MCS index values were positively elevated, but this was not reflected proportionally as expected on the DL user throughput values in comparison with other cities. One of the reasons for this phenomenon could be that the CL MIMO effect is not fully reflected due to high number of inter-cell handovers and possibly high interference levels (as in densely populated cities there are dense base station deployments).

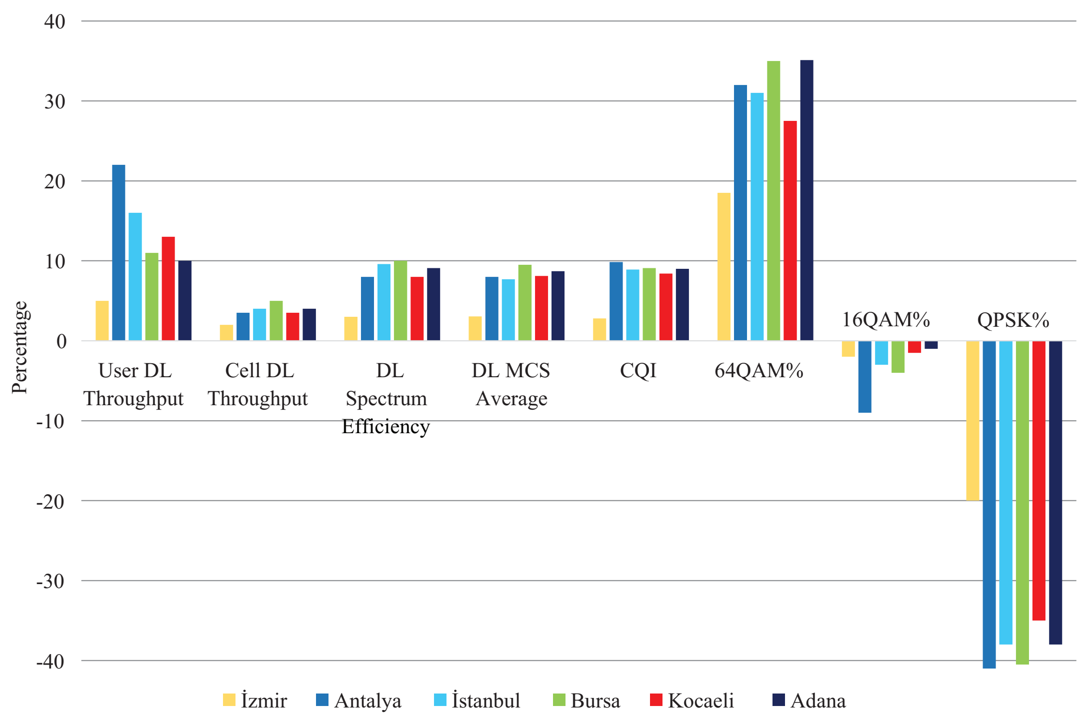

Figure 7. Overall KPIs and corresponding gains after closed-loop MIMO is activated in different cities of Turkey.

Main observations and takeaways: CL MIMO is expected to be utilized in combination with different evolving technologies in 5G networks. For this reason, it is essential to observe its potential benefits in comparison with OL MIMO scheme. Note that CL MIMO is a mechanism used to continuously adapt the transmitted signal to suit the channel characteristics, whereas, in OL MIMO, the communications channel does not utilize explicit information regarding the propagation channel. Hence, the success of CL MIMO scheme depends on the quality of channel estimation as the UE measures the channel to send reports back to BS. On the other hand, potential communication system impairments such as transmit & receive phase differences don't affect the performance of OL MIMO scheme. During the observation period of our practical experimental setup, overall improvements have been observed in major LTE KPIs including CQI, 64 QAM usage in DL, UE & cell throughput, spectral efficiency, packet delay, and IBLER values after switching MIMO scheme from OL to CL spatial multiplexing in the considered major cities of Turkey. CL MIMO is generally more efficient than OL MIMO in low mobility conditions where user's radio conditions don't change rapidly. This signifies that majority of the UEs inside the considered sites are in low mobility conditions. However, in locations where high mobility exists (e.g. in highways), it may be more suitable to proceed with OL MIMO scheme. Moreover, in specific locations where high amount of traffic is available, communication overhead of CL MIMO can deteriorate the obtained gains in terms of the considered KPIs. Therefore, an adaptive approach where appropriate switching capability between OL and CL MIMO transmission scheme can be necessary depending on the hour of the day (e.g. on peak or low hour traffic) or the characteristics of the locations (e.g. residential, business, shopping area, airport, etc.). On the other hand, the improvements in throughput values were also not too high (around 3% to 9%). This signifies low rank usage choice of BSs in CL MIMO scheme. Moreover, uncalibrated antennas can also cause for the differences in codeword-qualities. Theoretically, CL MIMO has been shown to provide up to 2dB theoretical link gain corresponding to up to 20% theoretical spectrum efficiency gain compared to OL MIMO schemes as demonstrated in [8] in ideal conditions. On the other hand, our experimental results have indicated that up to 6% for spectrum efficiency gain has been be achieved with CL MIMO scheme under real operation scenarios. This can be due to nonideal environments where many environmental factors, such as density of the cell, mobility, spatial and temporal patterns of user traffic, BS and UE antenna configurations, etc. as well as impairments related to differences in received signal's amplitude, timing/frequency offsets, and phase noise in CL MIMO at the BS site that have degraded the performance gains.

Note that OL transmit diversity can yield better performances at low SINR regimes, whereas OL & CL spatial multiplexing MIMO schemes can work better in high SINR regimes (as also demonstrated with system level simulations in [11]. Therefore, depending on the optimal SINR point, using transmit diversity or spatial multiplexing schemes need to be decided based on the KPI measurements. This can be beneficial for cities such as İzmir, which is observed to have the lowest MCS index and CQI values. Note also that potential 5G services that can be provided by mmWave (e.g. at 28 Ghz) spectrum can be affected by the surrounding environment, such as building shadowing, reflection, rain attenuation, etc. [33]. However, our frequency ranges of eNodeBs used throughout the experiments were on the order of 800 Mhz and 1800 Mhz. Therefore, the effect of such environmental factors, such as atmospheric conditions are not having a big impact on the performance of CL MIMO systems.

5. Conclusions

In this paper, we have run real-world experiments on OL and CL MIMO strategies. We have observed different KPIs that are of interest to MNOs. First, we have described the characteristics, limitations, and benefits of both MIMO transmission schemes. Then, we have run practical experiments to demonstrate the performance gain of CL MIMO in major and the most crowded cities of Turkey. Based on the obtained experimental results, CL MIMO is shown to outperform 3% OL MIMO for cell average throughput, 9% for user throughput, 6% for spectrum efficiency, 9% in CQI and MCS as well as 25% and 17% reductions on sum delay and IBLER. Therefore, CL MIMO is demonstrated to be a strong practical candidate technique for future wireless networks via a practical experimental set-up. A possible future study area can focus on the reducing the computational burden at the UE introduced by the CQI, RI, and PMI reporting via alternative channel estimation models such as channel transfer functions that are characterizing end-to-end performance. Additionally, an adaptive switch scheme between different MIMO modes, which can leverage the strengths of OL transmit diversity, OL & CL spatial multiplexing MIMO depending on radio environment, and observing their impact on large-scale nationwide deployments are of interest.

Acknowledgments

This work was funded by Spanish MINECO grant TEC2017-88373-R (5G-REFINE) and by Generalitat de Catalunya grant 2017 SGR 1195.

References

[1] 3GPP. Service Requirements for the 5G System Stage 1 (Release 17), TS 22.261 V16.6.0. Technical Specification Group Services and System Aspects, 2019.

[2] Chen Y, Bayesteh A, Wu Y, Han S, Taherzadeh, M et al. SCMA: A promising non-orthogonal multiple access technology for 5G networks. In: IEEE 84th Vehicular Technology Conference (VTC-Fall); Montreal, Canada; 2016. pp. 1-6.

[3] Vannithamby R, Talwar S. Towards 5G: Applications, Requirements and Candidate Technologies. New York, USA: John Wiley & Sons. 2017.

[4] Paleologu C. A preview on MIMO systems in 5G new radio. In: Future Access Enablers for Ubiquitous and Intelligent Infrastructures: Third International Conference; Bucharest, Romania; 2017. pp. 12-14.

[5] 3GPP. NR; User Equipment (UE) Radio Transmission and Reception; Part 1: Range 1 Standalone (Release 16), TS 38.101-1 V16.1.0. Technical Specification Group Services and System Aspects, 2019.

[6] Chen X, Benjebboui A, Lan Y, Li A, Jiang H. Evaluations of downlink non-orthogonal multiple access (NOMA) combined with SU-MIMO. In: IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication; Washington DC, USA; 2014. pp. 1887-1891.

[7] Busari SA, Mumtaz S, Al-Rubaye S, Rodriguez J. 5G millimeter-wave mobile broadband: performance and challenges. IEEE Communications Magazine 2018; 56(6):137-143. doi:10.1109/MCOM.2018.1700878.

[8] Olufemi JO, Baptiste V, Rodolphe V, Herve B. Performance analysis of closed-loop MIMO precoder based on the probability of minimum distance. IEEE Transactions on Wireless Communications 2015; 14(4):1849-1857. doi:10.1109/TWC.2014.2374593.

[9] Chen X. Experimental investigation and modeling of the throughput of a 2x2 closed-loop MIMO system in a reverberation chamber. IEEE Transactions on Antennas and Propagation 2014; 62(9):4832-4835. doi:10.1109/TAP.2014.2330599.

[10] O'Shea TJ, Erpek T, Clancy TC. Physical layer deep learning of encodings for the MIMO fading channel. In: 55th Annual Allerton Conference on Communication, Control, and Computing; Monticello, USA; 2017. pp. 76-80.

[11] Ball CF, Müllner R, Lienhart J, Winkler H. Performance analysis of closed and open loop MIMO in LTE. In: European Wireless Conference; Aalborg, Denmark; 2009. pp. 260-265.

[12] Shojaeifard A, Hamdi KA, Alsusa E, So DKC, Tang J. Performance analysis of multi-antenna HetNets. In: IEEE 83rd Vehicular Technology Conference (VTC Spring); Montreal, Canada; 2016. pp. 1-5.

[13] Kim I, Um J KA, Park S. Performance analysis of the key aspects affecting capacity of 4G LTE networks. In: International Conference on Information and Communication Technology Convergence; Jeju, South Korea; 2017. pp. 769-771.

[14] Pocovi G, Pedersen KI, Soret B. On the impact of precoding errors on ultra-reliable communications. In: International Workshop on Multiple Access Communications; Jeju, South Korea; 2016. pp. 45-54.

[15] Pedersen KI, Niparko M, Steiner J, Oszmianski J, Mudolo S et al. System level analysis of dynamic user-centric scheduling for a flexible 5G design. In: IEEE Global Communications Conference; Washington, DC, USA; 2016. pp. 1-6.

[16] Choi, J, Love DJ, Bidigare P. Downlink training techniques for FDD massive MIMO systems: open-loop and closed-loop training with memory. IEEE Journal of Selected Topics in Signal Processing 2014; 8(5):802-814. doi:10.1109/JSTSP.2014.2313020.

[17] Schulz B. LTE transmission modes and beamforming. White paper, Rohde & Schwarz, 2015.

[18] Sergeev V, Davydov A, Morozov G, Orhan O, Lee W. Enhanced precoding design with adaptive beam width for 5G new radio systems. In: IEEE 86th Vehicular Technology Conference (VTC Fall); Toronto, Canada; 2017. pp. 1-5.

[19] Yuksekkaya B and Toker, C. Joint transceiver FIR filter design for multiuser MIMO channel shortening equalization and full equalization using channel duality. Turkish Journal of Electrical Engineering & Computer Sciences 2017; 25(5):4077-4090. doi:10.3906/elk-1610-320.

[20] Cai L, Pelletier B, Zhang HO, Xi F. Power Control for Closed Loop Transmit Diversity and MIMO in Uplink. US10299227B2, US Patent, 2019.

[21] Tong W, JiaJianglei M, ZhuHua M, YuHang X, Fong, Z. Closed Loop MIMO Systems and mMethods. US9271221B2, US Patent, 2016.

[22] PoratWee R,Goh, WP,Bourlas Y. Closed Loop MIMO Harmonized Feedback. US9608703B2, US Patent, 2017.

[23] Frenger Pål, Jöngren G, Parkvall S. Switching Between Open and Closed loop Multi-stream Transmission. US968514836, US Patent, 2013.

[24] Sezgin G, Coskun Y, Basar E, Kurt GK. Performance evaluation of a live multi-site LTE network. IEEE Access 2018; 6(1):49690-49704. doi:10.1109/ACCESS.2018.2868385.

[25] Sharda P, Singh H, Sheetal A. Optimisation of LTE system with open-and closed-loop spatial multiplexing transmission modes. Australian Journal of Electrical and Electronics Engineering 2017; 14(3):88-92. doi:10.1080/1448837X.2018.1465375.

[26] Bhaskar V, John AA. Performance modelling of open loop and closed loop multiuser multiple-input multiple-output-orthogonal frequency division multiplexing systems through channel analysis. IET Communications 2015; 9(11):1355-1366. doi:10.1049/iet-com.2014.0613.

[27] Björnson E, Hoydis J, Sanguinetti L. Massive MIMO networks: spectral, energy, and hardware efficiency. New York, USA: Now Foundations and Trends. 2017.

[28] 3GPP. LTE Evolved Universal Terrestrial Radio Access (E-UTRA) Physical Layer Procedures (Release 12), TS 36.213 V15.7.0. Technical Specification, 2019.

[29] 3GPP. Radio Frequency (RF) System Scenarios (Release 15), TS 25.942 V15.0.0. Technical Specification, 2018.

[30] Turk Y, Zeydan E, Akbulut CA. Experimental performance evaluations of CoMP and CA in centralized radio access networks. Telecommunication Systems 2019; 9(11):1355-1366. doi:10.1007/s11235-019-00553.

[31] Turk Y, Zeydan E, Akbulut CA. On performance analysis of single frequency network with C-RAN. IEEE Access 2018; 7(1):1502-1519. doi:10.1109/ACCESS.2018.2887005.

[32] 3GPP. Base Station (BS) cConformance Testing (Release 16), TS 36.141 V16.5.0. Technical Specification, 2020.

[33] Etinger A, Golovachev Y, Shoshanim O, Pinhasi GA, Pinhasi Y. Experimental study of fog and suspended water effects on the 5G millimeter wave communication channel. Electronics 2020; 9(5):720-737. doi:10.3390/electronics9050720.