SISO and MIMO Throughput Analysis for Long Term Evolution (LTE)

Siti Zuraini Binti Harun
Faculty of Electrical Engineering
Universiti Teknologi MARA (UiTM)
Shah Alam, Selangor, Malaysia
sitizurainiharun@hotmail.com

Abstract—**This paper provides the analysis and comparison of data throughput in Long Term Evolution (LTE) between Single Input Single Output (SISO) and Multiple Input Multiple Output (MIMO). LTE utilizes MIMO data transmission such as Open Loop (OL) Spatial Multiplexing, Close Loop (CL) Spatial Multiplexing, Transmit Diversity and Single Input Multiple Output (SIMO) in achieving higher data throughput and channel capacity as compared to SISO conventional transmission scheme. Based on the results obtained using base station emulator equipment, the performance of physical layer data throughput is evaluated for different conditions and scenarios, which the following are being considered such as various antenna diversity schemes for instance 2x2 antenna configuration, different modulation, coding schemes, bandwidth and resource block. The effect of changing the mentioned parameters will result to a different throughput and impact radio performance. For this, a thorough analysis has been done comparing both cases SISO and MIMO using a commercial LTE device which is now available in the market. The performance study and test includes FDD operational mode for uplink and downlink transmission.**

Key Words—**Throughput, Long Term Evolution (LTE), Single Input Single Output (SISO), Multiple Input Multiple Output (MIMO)**

I. INTRODUCTION

LTE is the evolutionary step towards 4th generation (4G) mobile to cope up with the increasing throughput requirements of the future wireless cellular systems [1]. The first commercial LTE services started at the end of 2009 and since then the deployment has continued to grow rapidly. For country like Malaysia, it begun in the Year 2013 by recognizing eight telecommunication companies mainly network operators for the LTE deployment. LTE main focus is to greatly improve end-user throughputs in acquiring higher data rates, reduce user plane and control plane latency and increase sector capacity. However, only end-user throughput analysis will be the main focus of this paper. In order to fulfill the requirements of LTE, it uses new multiple access schemes. The Uplink and Downlink use OFDMA and SC-FDMA respectively. Furthermore, MIMO transmission scheme has been formulated as the essential part of LTE where this technology capably boosts up the data throughput without the need of additional bandwidth and transmit power. It includes both FDD and TDD mode of operations.

LTE focus on supporting packet switched (PS) services at the optimum. The data rate has been specified to achieve of 100Mbps in the downlink and 50Mbps in the uplink for maximum bandwidth of 20MHz spectrum allocation. With this, the targeted throughput for downlink should be 3 to 4 times better and uplink with 2 to 3 times better than 3GPP Release 6.

Moreover, the crucial part of LTE in succeeding the ambitious requirements for throughput is Multiple Input Multiple Output (MIMO). Multiple Input Multiple Output (MIMO) system uses more than one transmit antenna to send a signal on the same frequency to more than one receive antenna [3]. It is planned to significantly boost the data rates and overall system capacity. For LTE downlink, a 2x2 configuration for MIMO is assumed and will be tested as baseline configuration. MIMO succeeds under rich scattering conditions where signals bounce around. The transmitted signals use multiple paths to reach the user equipment (UE) at different times. This multipath scenario is also been simulated in the base station emulator equipment and throughput of this condition will then be observed. MIMO is built on SIMO which is also called the receive diversity and as well as MISO, known as the transmit diversity. Both of the techniques have the same aim to boost the signal-to-noise ratio (SNR) in order to compensate the signal degradation under multipath propagations and fading scenario. The multiple antenna system can compensate for some of the SNR loss due to multipath conditions by combining signals that have different fading characteristics, since the path from each antenna will be slightly different. The effect of enhancing the signal to noise ratio will then lead to the increase of data rates by using a higher modulation scheme such as 64-QAM and 16-QAM rather than QPSK. The achievement of the data rates will be tested using the base station emulator equipment by configuring to a different modulation scheme.

Different gains can be achieved depending on the MIMO mode that is used such as spatial multiplexing and transmit diversity. In spatial multiplexing, each transmitter sends a different data stream to multiple receivers. These data streams are reconstructed separately by the user equipment (UE). It may seem unbelievable that two signals sent at the same time and frequency within the same sector can result in the increased of throughput rather than interference. The analogy of MIMO is similar to conventional spectrum re-use where signals are transmitted in the same frequency in different cells. For spectrum re-use, the cells must be far enough and have to occupy different space in order to avoid interference. With spatial multiplexing, the signals have to occupy different space time in the same cell instead of occupying a different cell. In spatial multiplexing, multiple data streams are transmitted with the same transmit power. It distributes the total SNR between the data streams, each of which has a lower power level. With this, each of the multiple data streams may be capable of transmitting nearly as much data as a single stream.

Theoretically, the result of spatial multiplexing multiplies the throughput by the transmission rank. With the 2x2 antenna configuration in Multiple Input Multiple Output (MIMO) which is tested, the expected result is actually doubles up the throughput both for individual users and for each cell as a whole compared to Single Input Single Output (SISO) transmission scheme. On the other hand, the implementation of this in order to achieve high throughput depends on three factors; maximize scattering conditions within cell, configure eNodeB (base station) to properly match Multiple Input Multiple Output (MIMO) settings and ensure User Equipment (UE) can take the full advantage of multipath conditions that are present. With these measurements, network operators can maximize the data rates and reliability of Long Term Evolution (LTE) networks resulted to a good return in LTE equipment investments while improving customer satisfaction. In the downlink, LTE uses technologies such as MIMO to achieve high data rates. However, it also offers fallback technologies such as SISO. In Multiple Input Multiple Output (MIMO) system, a complex fading channel exists between each transmit and receive antenna pair. While the performance of a Single Input Single Output (SISO) system degraded by the fading process since only one transmit and one receive antenna used. With this, Multiple Input Multiple Output (MIMO) system works best under multipath conditions.

Besides increasing the throughput, Multiple Input Multiple Output (MIMO) can be used to exploit diversity and increase the robustness of data transmission. Transmit diversity is also part of LTE where each transmit antenna transmits essentially the same stream of data. This increases the Signal-to-Noise Ratio (SNR) at the receiver side and thus the robustness of data transmission in fading scenarios.

II. SINGLE INPUT SINGLE OUTPUT (SISO)

The conventional way of one transmitting and one receiving is known as Single Input Single Output (SISO). The below Fig. 1 depicts the SISO block diagram.

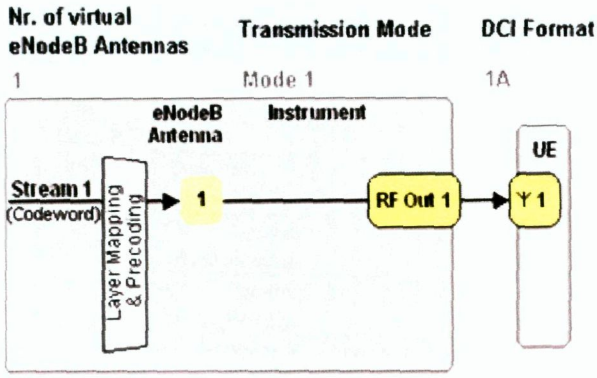

Fig. 1: SISO Block Diagram

Mainly, the term input and output refer to the transmission channel. Input normally is a transmitting antenna of the base station and the output is actually the receiving antenna of User Equipment (UE). For instance, downlink refers to the transmission channel from base station emulator equipment to the user equipment (UE).

III. MULTIPLE INPUT MULTIPLE OUTPUT (MIMO)

It is widely known that Multiple Input Multiple Output (MIMO) provides substantial improvement to data rate and channel capacity. MIMO transmission scheme is crucial for LTE downlink in acquiring high throughput requirement. Fig. 2 illustrates the MIMO system block diagram for 2x2 antenna configurations. It simply means that two antennas are used at transmitter side (input) and as well as two antennas at the receiver side which act as output.

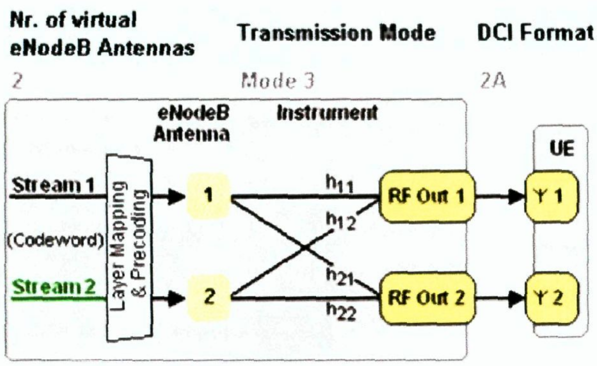

Fig. 2: MIMO Block Diagram

There are few MIMO modes defined under MIMO transmission schemes such as Spatial Multiplexing for Close Loop (CL) and Open Loop (OL), Transmit diversity, and Receive diversity.

Spatial multiplexing uses 2x2 antenna configurations which mean two transmit and two receive antennas used. This mode allows two data streams being transmitted simultaneously using the same resource blocks (RB). This is clearly shown in Fig. 2. The difference between Open Loop and Close Loop is the User Equipment (UE) feedback to the eNodeB (base station emulator equipment) for Close Loop where UE estimates the radio channel and selects the optimum matrix. Open Loop spatial multiplexing does not require UE feedback and eNodeB (base station emulator equipment) chooses a matrix.

Transmit diversity transmits the same data stream and uses several transmitting antennas. The advantage of this mode is basically increasing the robustness of data transmission by having a high Signal-to-Noise Ratio (SNR). Fig. 3 shows the Transmit diversity block diagram.

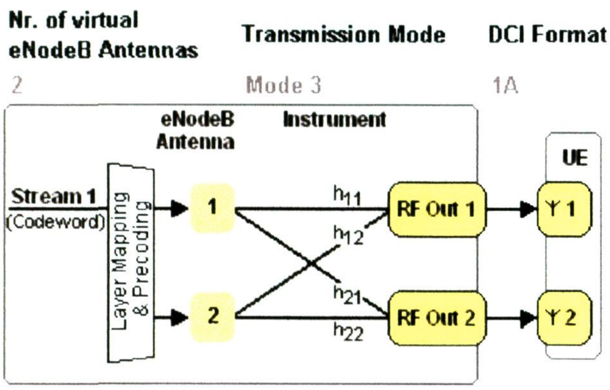

Fig. 3: Transmit Diversity Block Diagram

Receive diversity mainly receives same data stream at receiver side with the aid of more than one antenna being used. This configuration increases the Signal-to-Noise ratio (SNR). The below Fig. 4 captured the Receive diversity or also known as SIMO block diagram.

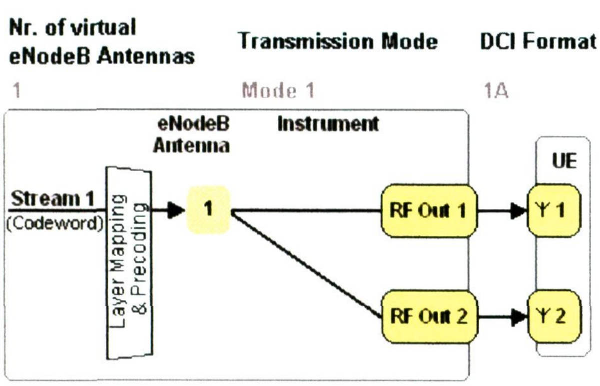

Fig. 4: Receive Diversity (SIMO) Block Diagram

In summary, the transmission schemes involved in determining the throughput of this study are as listed in Table 1 and it is in accordance to the 3GPP standard and specifications. Test conducted using Base Station Emulator test equipment and commercial LTE Dongle which available in the market.

Scenario	Transmission Scheme	Data Streams	TX x RX Antennas
Standard Cell	SISO	1	1 x 1
Two RF Out Ports	SIMO	1	1 x 2
	Transmit Diversity	1	2 x 2
	OL Spatial Multiplexing	2	2 x 2
	CL Spatial Multiplexing	2	2 x 2

Table 1: Transmission Scheme Overview

IV. LTE SIGNALING

The reason of using base station emulator equipment is to emulate the Evolved Universal Mobile Telecommunications System Terrestrial Radio Access Network (E-UTRAN) cell and communicate with the commercial LTE dongle under test. In order to comply with the 3GPP standard, a connection setup of Reference Measurement Channel (RMC) or User Defined Channel is necessary on the instrument.

SISO measurement requires basic test setup for a standard cell scenario. The connection is done between the base station emulator equipment and the device under test (DUT) which is the LTE dongle. This setup allows carrying both uplink and downlink signals. Measurement started by the base station emulator equipment as it transmits the downlink (DL) signal to the DUT. At this stage, DUT looks for synchronization in order to perform an attach to the base station emulator equipment. Basically, the downlink (DL) signal is used to transfer user data and signaling messages to DUT. Next, DUT will then transmits the uplink (UL) signal which should be received and decode for the purpose of setting up the connection and perform various measurements to the base station emulator equipment. The test setup for SISO measurement can be visualized in Fig. 5.

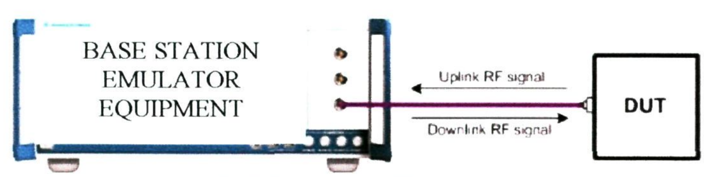

Fig. 5: Test Setup for SISO

The test setup for MIMO measurement requires to be done under "Two RF Out Ports" scenario on the base station emulator equipment. Antenna configurations of 2x2 distinguish that two antennas used at both transmit and receive. It involves two uplink (UL) and two downlink (DL) signals at UE side. This scenario is done in the base station emulator equipment by transmitting the two downlink signals using a different transmit (TX) module which resulted to two different paths. The test setup for MIMO is illustrated in Fig. 6.

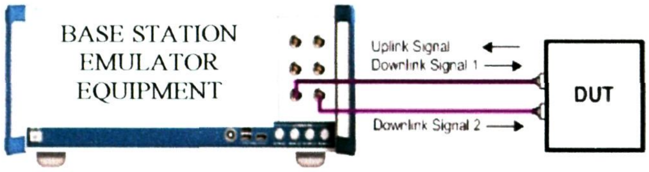

Fig. 6: Test Setup for MIMO

Most of the measurement steps either SISO or MIMO can be generally outlined as depicted in Fig. 7:

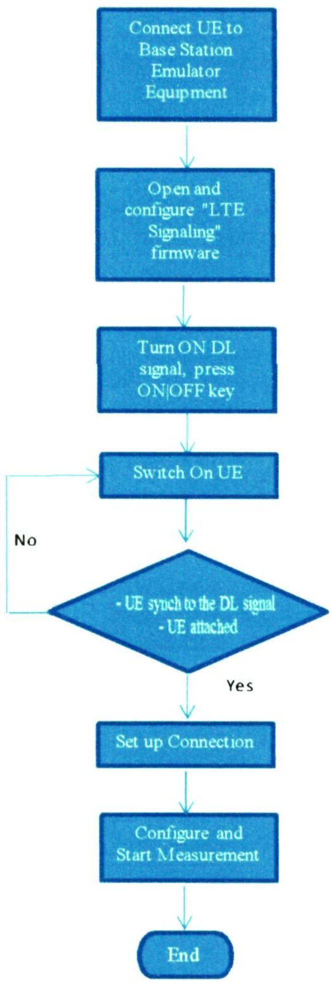

Fig. 7: Measurement Procedures

The base station emulator equipment provides packet switch connection states for LTE core network. At this stage it gives the indication of LTE dongle under test and the connection states are described as in Table 2.

Packet Switch State	Description
Cell OFF	No DL signal transmission
Cell ON	The base station emulator equipment emulates the E-UTRAN cell. It transmits the LTE signal which UE can synchronize. After synchronization, UE initiates the attach procedure with the instrument
Attached	Established a default bearer where synchronization and attach procedures are completed
Connection Established	Dedicated bearer established and user data can be exchanged via shared channels

Table 2: LTE Core Network Packet Switch Connection States

The below Fig. 8 expresses the possible packet switch state transitions of LTE core network:

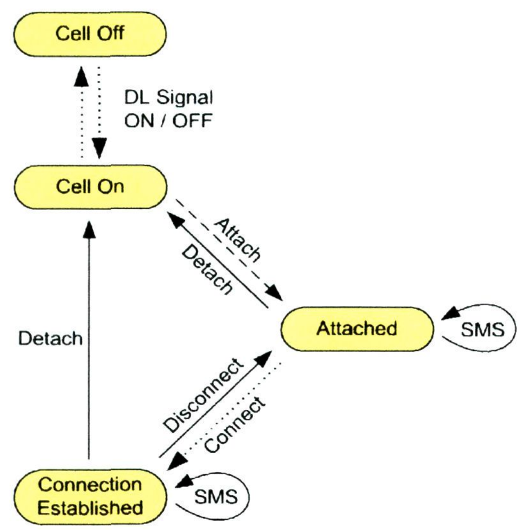

Fig. 8: LTE Packet Switch State Transitions

V. EXTENDED BLER AND THROUGHPUT MEASUREMENTS

In LTE, the measurement of Extended Block Error Ratio (BLER) is determined when data is sent to UE via Physical

Downlink Shared Channel (PDSCH). The throughput is calculated based on the positive acknowledgement (ACK) and negative acknowledgement (NACK) which is reverted by UE.

The measurement commences when the base station emulator equipment sends data to UE via Physical Downlink Shared Channel (PDSCH) and request UE to confirm the correct reception. This is being tabulated in the form of ACK and NACK where the subframe is received via Physical Uplink Shared Channel (PUSCH). Transmission schemes listed in Table 1 either that use of several downlink streams or not are evaluated separately

Throughput is calculated based on the BLER results. Mainly, it displays the maximum throughput in Mbit/s and calculated over the downlink and uplink stream. The derivation of throughput can be simplified as the number of received ACK multiplied with bits per transport block and divided by the time. From the resulted values of throughput, the instrument defines the maximum, average and minimum values.

VI. RESULTS AND DISCUSSION

In this section, the performance of physical layer data throughput is evaluated under different conditions and scenarios. Mainly, tests are conducted for Single Input Single Output (SISO), Open Loop Spatial Multiplexing, Close Loop Spatial Multiplexing, Transmit Diversity and Single Input Multiple Output (SIMO) which also known as Receive Diversity. Each of tests will be discussed in this section and as well as its settings and results.

The following Fig. 9 and Fig. 10 show the test settings summary and result for SISO testing respectively. Mainly, test scenarios covered FDD operating mode, and both LTE bandwidth supported by LTE Dongle under test which are 10 MHz and 20 MHz correspondingly. Test conditions covered different modulation schemes being used for both uplink and downlink, resource block allocation for different bandwidth requirements which indirectly resulted to SISO throughput measurement.

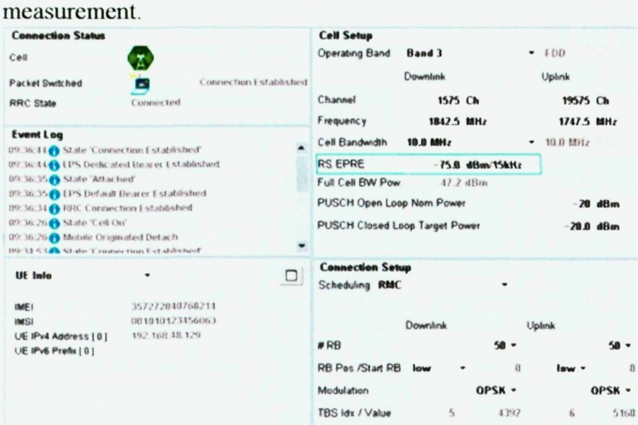

Fig. 9: SISO Test Settings – General Overview

From the test result presented in Fig. 10, it shows significant improvement interms of throughput for 20 MHz bandwidth used as compared to 10 MHz bandwidth. The throughput value captured for 20 MHz bandwidth is almost doubles than the 10 MHz value for both modulation schemes namely QPSK and 64-QAM. For instance, 10 MHz bandwidth under QPSK modulation scheme captured 3.83 Mbps as compared to 20 MHz bandwidth of 7.6 Mbps. This is also proven and comparable to the calculated values of 3.953 Mbps and 7.884 Mbps for 10 MHz and 20 MHz respectively. Throughput value degradation is expected as under real operating condition, setup is prone to interference and multipath fading. The full throughput test result of SISO measurement under different modulation schemes, bandwidth and resource block is tabulated in Table 3 below.

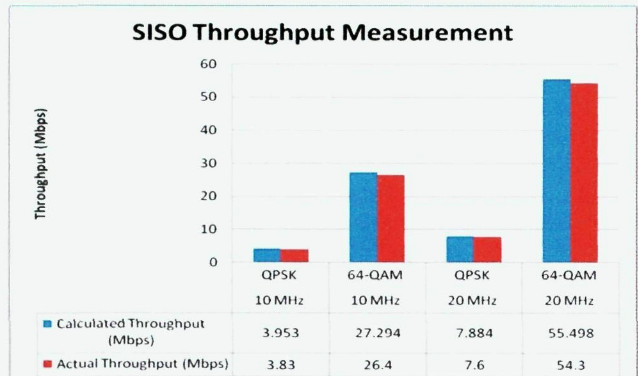

Fig. 10: SISO Throughput Measurement

Transmission Scheme	Bandwidth	Resource Block	Modulation		Throughput (Mbps)	
			Downlink	Uplink	Calculated Throughput (Mbps)	Actual Throughput (Mbps)
SISO	10 MHz	50	QPSK	QPSK	3.953	3.83
			64-QAM	16-QAM	27.294	26.4
	20 MHz	100	QPSK	QPSK	7.884	7.6
			64-QAM	16-QAM	55.498	54.3

Table 3: SISO Throughput Test Result

Fig. 11 and Fig. 12 depict the MIMO Open Loop and Close Loop spatial multiplexing throughput measurement individually. The throughput of both transmission schemes are perceived to be comparable as it is tested under the same antenna configuration which is in the matrix of 2x2. Under MIMO condition, two data streams are being transmitted simultaneously and resulted to a high data throughput. In dissimilarity to SISO, MIMO transmission channel consists of four individual paths and can be represented as four complex-valued matrix elements

The factor of achieving high data throughput is also depending on modulation scheme used such as 64-QAM. Higher modulation provides higher data throughput but it is also prone to noise as compared to a low modulation scheme such as QPSK where it seems to be more robust. In other words, low modulation scheme provides better Signal-to-Noise ratios which make it more robust as compared to high modulation.

Based on the result obtained, it is observed that the throughput is different for both Fig. 11 and Fig. 12 in the case of 16-QAM with 20 MHz requirement. This is due to the different transport block size (TBS) setting used. The change of TBS value points to a different code rate being used. Higher TBS value used lead to a higher data throughput as seen on MIMO – Open Loop spatial multiplexing graph as compared to Fig. 12 for the same condition. An approximate throughput of 102.05 Mbps under 64-QAM modulation scheme for MIMO - Open Loop spatial multiplexing proved that the LTE dongle device under test simply met one of the focus in LTE where data rate has been specified to achieve of 100Mbps in the downlink.

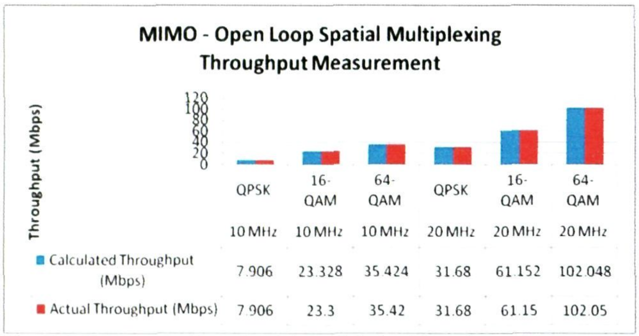

Fig. 11: MIMO – Open Loop Spatial Multiplexing Throughput Measurement

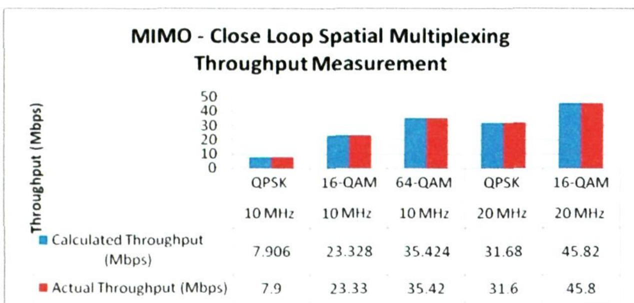

Fig. 12: MIMO – Close Loop Spatial Multiplexing Throughput Measurement

The detailed MIMO results for both Close Loop and Open Loop mode are tabulated in the following Table 4 and Table 5.

Transmission Scheme	Bandwidth	Resource Block	Modulation		Throughput (Mbps)	
			Downlink	Uplink	Calculated Throughput (Mbps)	Actual Throughput (Mbps)
MIMO - OL Spatial Multiplexing	10 MHz	50	QPSK	QPSK	7.906	7.906
			QPSK	16-QAM	7.906	7.9
			16-QAM	QPSK	23.328	23.3
			16-QAM	16-QAM	23.328	23.3
			64-QAM	QPSK	35.424	35.42
			64-QAM	16-QAM	35.424	35.42
	20 MHz	100	16-QAM	QPSK	45.82	45.82
			16-QAM	16-QAM	45.82	44.98
			64-QAM	16-QAM	102.048	102.05
			QPSK	QPSK	31.68	31.68
			QPSK	16-QAM	31.68	31.68
			16-QAM	QPSK	61.152	61.15
			16-QAM	16-QAM	61.152	61.15

Table 4: MIMO – OL Spatial Multiplexing Throughput Test Result

Transmission Scheme	Bandwidth	Resource Block	Modulation		Throughput (Mbps)	
			Downlink	Uplink	Calculated Throughput (Mbps)	Actual Throughput (Mbps)
MIMO - CL Spatial Multiplexing	10 MHz	50	QPSK	QPSK	7.906	7.9
			QPSK	16-QAM	7.906	7.9
			16-QAM	QPSK	23.328	23.33
			16-QAM	16-QAM	23.328	23.3
			64-QAM	QPSK	35.424	35.42
			64-QAM	16-QAM	35.424	35.42
	20 MHz	100	QPSK	QPSK	31.68	31.6
			16-QAM	QPSK	45.82	45.8
			16-QAM	16-QAM	45.82	45.8

Table 5: MIMO – CL Spatial Multiplexing Throughput Test Result

Next, transmit diversity is part of MIMO transmission scheme. The advantage of this mode is basically increasing the robustness of data transmission by having a high Signal-to-Noise Ratio (SNR). Better SNR thus provides robustness to data transmission.

Based on the test result as depicted in Fig. 13, it shows a slight difference between the theoretical and actual value for 16-QAM modulation and 20 MHz bandwidth. The dissimilarity is due to external fading. This scenario is demonstrated in Fig. 14 where it shows the positive and negative acknowledgements namely ACK and NACK respectively. The testing returns only 99.81% of successful reception while the remaining 0.19% is the error rate which resulted to actual throughput reading of 22.87 Mbps at average. For 10 MHz bandwidth, the throughput is comparable between theoretical and actual measured values for the specified modulation schemes of QPSK, 16-QAM and 64-QAM.

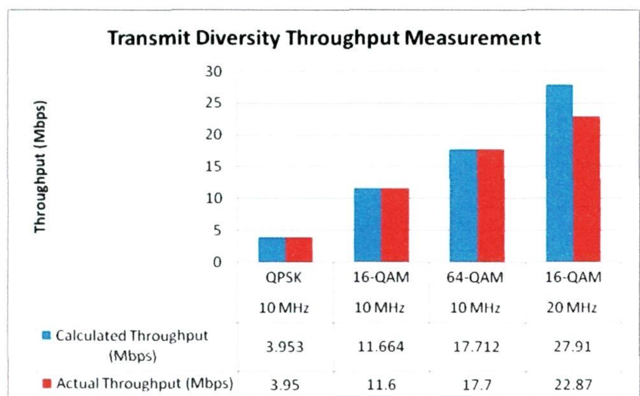

Fig. 13: Transmit Diversity Throughput Measurement

Fig. 14: Transmit Diversity Throughput Measurement Result

Table 6 illustrates the test results of transmit diversity throughput measured under few conditions.

Transmission Scheme	Bandwidth	Resource Block	Modulation		Throughput (Mbps)	
			Downlink	Uplink	Calculated Throughput (Mbps)	Actual Throughput (Mbps)
TX Diversity	10 MHz	50	QPSK	QPSK	3.953	3.95
			QPSK	16-QAM	3.953	3.95
			16-QAM	QPSK	11.664	11.6
			16-QAM	16-QAM	11.664	11.6
			64-QAM	QPSK	17.712	17.7
			64-QAM	16-QAM	17.712	17.7
	20 MHz	100	16-QAM	QPSK	22.91	22.87
			16-QAM	16-QAM	22.91	22.87

Table 6: Transmit Diversity Throughput Test Result

Single Input Multiple Output (SIMO) performs slightly better than transmit diversity interms of throughput derivation. This can be clearly compared between Fig. 15 and Fig. 13 for data which belongs to 64-QAM modulation and 10 MHz bandwidth. Furthermore, the throughput is observed to be approximately doubled if bandwidth is doubled. This is proven for 64-QAM modulation for both 10 MHz and 20 MHz bandwidth which result to 27.29 Mbps and 55.4 Mbps separately.

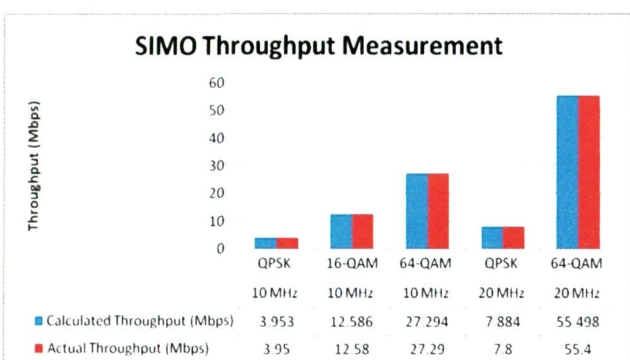

Fig. 15: SIMO Throughput Measurement

Full test result of SIMO throughput measurement is organized as follow in Table 7.

Transmission Scheme	Bandwidth	Resource Block	Modulation		Throughput (Mbps)	
			Downlink	Uplink	Calculated Throughput (Mbps)	Actual Throughput (Mbps)
SIMO	10 MHz	50	QPSK	QPSK	3.953	3.95
			QPSK	16-QAM	3.953	3.95
			16-QAM	QPSK	12.586	12.58
			16-QAM	16-QAM	12.586	12.58
			64-QAM	QPSK	27.294	27.29
			64-QAM	16-QAM	27.294	27.29
	20 MHz	100	QPSK	QPSK	7.884	7.8
			QPSK	16-QAM	7.884	7.8
			64-QAM	QPSK	55.498	55.4
			64-QAM	16-QAM	55.498	55.4

Table 7: SIMO Throughput Test Result

The last part of the analysis shows a different throughput values between MIMO transmission schemes. This is resulted from a different code rate and TBS being used and it is observed in each transmission scheme. Test conducted for 64-QAM DL and 16-QAM UL with 20 MHz bandwidth allocated for all transmission schemes as specified in Fig.16. The same result of different transport block size used is also represented in Fig.17. The actual measurement shows a further degradation of throughput than theoretical values due to fading effects and noise existence in the surrounding areas. Higher modulation scheme such as 64-QAM seems to carry more data, however less robust interms of data transmission as compared to a lower modulation scheme of QPSK.

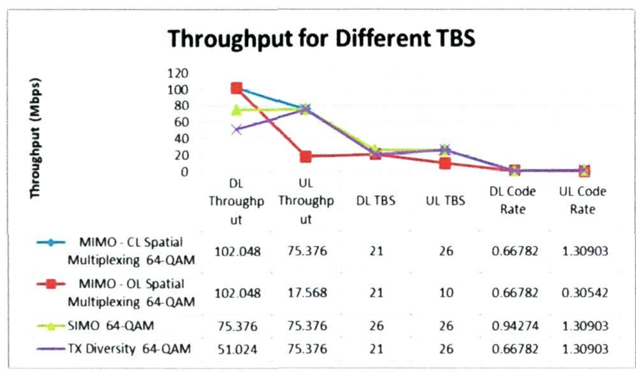

Fig. 16: Throughput for Different TBS

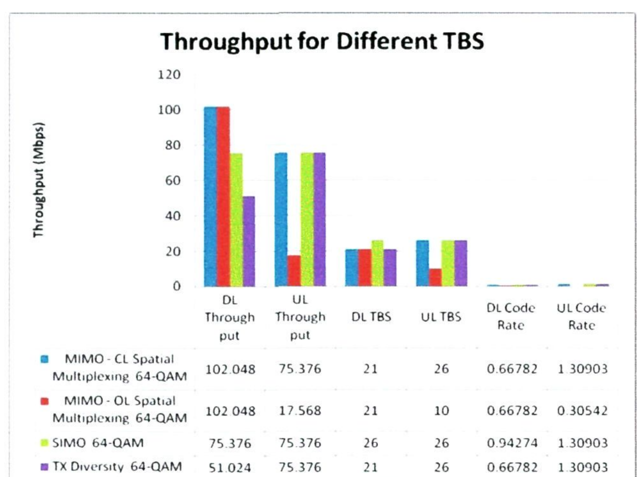

Fig. 17: Throughput for Different TBS

VII. CONCLUSION

This paper summarizes LTE throughput analysis under FDD operational mode for Single Input Single Output (SISO) and Multiple Input Multiple Output (MIMO). LTE utilizes MIMO data transmission such as Open Loop Spatial Multiplexing, Close Loop Spatial Multiplexing, Transmit Diversity and Single Input Multiple Output (SIMO) in achieving higher data throughput and channel capacity as compared to SISO conventional transmission scheme. Basically, the results obtained using base station emulator equipment, where the performance of physical layer data throughput is evaluated for different conditions and scenarios, and the following are being considered such as various antenna diversity schemes for instance 2x2 antenna configuration, different modulation, coding schemes, bandwidth and resource block. The effect of changing the mentioned parameters will result to a different throughput performance. Throughput comparison held for all MIMO transmission schemes and it is observed that the throughput is doubled as bandwidth doubled. Higher modulation scheme is prone to interference and fading effect due to low Signal-to-Noise ratio (SNR) level. Resource block allocation is directly related to bandwidth in used and it doubles the value as bandwidth is being doubled. The presented results show that the LTE dongle device worked well for maximum 100 Mbps in the downlink and at least 50 Mbps in the uplink for maximum bandwidth of 20 MHz. The data rate has been specified to achieve the LTE target throughput. MIMO open loop and close loop spatial multiplexing provide the highest throughput as compared to the remaining transmission schemes covered in this paper. SIMO performs slightly better throughput than transmit diversity. Furthermore, a different method has been selected in performing the throughput comparison analysis between SISO and MIMO. Base station emulator test equipment is used for eNodeB simulation and a commercial LTE dongle device is planned for user equipment (UE). Therefore, it simulates the real network environment and the performance of physical layer data throughput is then evaluated. This is in contrast to most of the papers published where a Matlab simulation is used for the same objective in performing the throughput analysis.

ACKNOWLEDGMENT

Thanks to Rohde & Schwarz for the chance of using such a fantastic equipment which is the CMW500 Wideband Radiocommunication Tester.

REFERENCES

[1] Suratia, Pooja S; Shah, Satish.K, "Performance Analysis of Open Loop and Closed Loop Spatial Multiplexing in LTE Downlink Physical Layer", 2012 IEEE International Conference, 2012

[2]http://cdn.rohdeschwarz.com/dl_downloads/dl_application/application_notes/1ma111/1MA111_4E.pdf

[3]http://rfsolutions.pctel.com/artifacts/MIMOWhitePaperRevB-FINAL.pdf

[4]http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1094&context=computerelectronicfacpub

[5] Adigun, O.; Politis, C."Energy efficiency analysis for MIMO transmission schemes in LTE" 2011 IEEE International Conference, 2011

[6] Tao Tao, "Performance analysis of Link Adaptation in LTE systems" 2011 IEEE International Workshop, 2011

[7] Ball, C.; Hindelang, T.; Kambourov, I.; Eder, S."Spectral efficiency assessment and radio performance comparison between LTE and WiMAX "2008 IEEE 19th International Symposium, 2008

[8] Rezaei, F.; Hempel, M.; Sharif, H."LTE PHY performance analysis under 3GPP standards parameters" 2011 IEEE 16th International Workshop, 2011