Comparison of LTE Network Download Upload FDD and TDD Technology

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Abstract – *Data communication like download and upload are mostly used in utilizing downlink and uplink channel in data transceiver. This research analyzed comparison of download and upload Time Division Duplex (TDD) 2100 Mhz and Frequency Division Duplex (FDD) 2300 Mhz under bandwith 20 MHz using drive test. Based on The Key Performance Indicator (KPI) of Telkomsel, average Reference Signal Received Power (RSRP) of FDD is better with very good category (-95 until -80 dBm) amounted -91.4 dBm and -89.4 dBm, while TDD namely -98,2 dBm dan -97,6 dBm. Average signal to Interference Noise Ratio (SINR) of TDD was better include into very good category (10 until 20 dB) amounted 13.4 dB and 12.1 dB, while FDD namely 8,9 dB dan 7,4 dB. Average Throughput Download in PDCP (Packet Data Convergence Protocol) and Physical Layer TDD was better with very good category (500 until 100000 kbps) namely 22457.3 kbps and 26842.3 kbps, while FDD namely 18687.7 kbps and 21790.6 kbps. Average Throughput Upload in PDCP and Physical Layer FDD was better, included into very good category (3000 – 5000 kbps) namely 3733.12 kbps and 4425.9 kbps, while TDD reached 2832.34 kbps and 3175.4 kbps. The research result showed that the best parameter in FDD (RSRP and Throughput Upload) and TDD (SINR, CQI, Throughput Download), fulfilled KPI Very Good Category*.

Keywords*: download, Frequency Division Duplex, Long Time Division Duplex, Time Division Duplex, Upload*

1. Introduction

Data communication needs are increasing, such as the use of social media for live streaming via Internet services. As a result, optimal performance on the downlink and uplink of 4G LTE technology services is required. LTE technology provides a downlink data transfer rate of 100 Mbps and an uplink data transfer rate of 50 Mbps [1], [2] . Orthogonal frequency division multiplexing (OFDM) is the multiplexing technique utilised, which is compatible with high-speed data and enhances communication quality[3]. The downlink modulation approach is OFDMA (Orthogonal Frequency Division Multiple Access), which allows simultaneous sharing between users in the time and frequency domains [4]–[8]. The usage of OFDMA might increase the Peak Average Power Ratio (PAPR), which reduces the efficiency of transmission power and necessitates high transmit power [5], [9], [10] As a result, the uplink employs Single Carrier Frequency Division Multiple Access (SCFDMA) using the Discrete Fourier Transform [10], [11] Furthermore, the SC-FDMA system offers a longer battery life [4], [10].

Time Division Duplex technology, Frequency Division Duplex, and a combination of both TDD and FDD (Advanced) technologies are used in 4G LTE technology [12]. TDD technology enables uplink and downlink channels to use the whole frequency spectrum in various time slots [13], [14]. This technique enables data to be broadcast and received in the same frequency channel with a brief time delay between them. Because the use of downlink channels is greater than that of uplink channels, TDD technology is the best solution because it can be configured to compare the use of downlink and uplink channels [15]. FDD technology employs two different carrier frequencies: one for transmission from the user (uplink) and one for reception by the user (downlink) [16]. The balance between downloading and uploading data is good as a result of using different frequencies for sending and receiving FDD technology [15]. Furthermore, adaptive modulation and coding serve as a coding and modulation scheme that correlates to the channel quality indicator (CQI) [17], [18]. LTE network modulation schemes include 64 QAM, 16 QAM, and QPSK [19], [20]. Good channel quality results in a large modulation order, coding rate, and bit rate capacity, and vice versa.

Research comparing LTE network performance between FDD and TDD technologies is vital for network optimization, spectrum efficiency, enhancing user experience, cost-effective deployment, future planning, and maintaining a competitive edge in the telecommunications industry. Understanding the strengths and limitations of FDD and TDD becomes essential for making informed decisions about network upgrades and expansions. For telecommunications companies, staying ahead of the competition is crucial. Researching and understanding the performance differences between FDD and TDD technologies can provide a competitive advantage by enabling companies to offer better services and improve customer satisfaction.

There has been little research into comparing download and upload results for 4G LTE networks. A previous study has been conducted on the coverage area of FDD and TDD technologies. However, this study did not compare the downlink and uplink on 4G LTE technology. Furthermore, only RF (Radio Frequency) metrics such as Reference Signal Receive Power, Signal Interference Noise Ratio, and Reference Signal Received Quality are still used in the study. This study's contribution is limited to comparing the coverage area of 4G LTE FDD and TDD technologies using these three parameters. As a result, it is critical to continue this research with additional contributions, namely comparing the performance of the two LTE TDD technologies at 2300 MHz and FDD at 2100 MHz with the same bandwidth of 20 MHz using RF parameters as well as Throughput at the Packet Data Convergence Protocol (PDCP) and Physical Layer layers (PHY) on the downlink and uplink sides. Thus, data collection was carried out through a driving test to obtain download and upload data in real-time in the field to analyze the differences in the downlink and uplink TDD and FDD technologies.

2. Research Method

Drive Test is a data-collection activity that measures the radio signal received by a subscriber's mobile in real time to analyse cellular network performance and attempts to improve network quality [21], [22]. This study employs driving test software, TEMS Pocket, and logfile data analysis tools, TEMS Discovery. LTE FDD with a frequency of 2100 MHz and LTE TDD with a frequency of 2300 MHz and a bandwidth of 20 MHz are used. Route Design is an important thing before doing drive test, it used Google Earth. The output of drive test is a logfile, and it is utilized to compare download and upload results between TDD and FDD technologies. The parameter employed was the Reference Signal Received Power (RSRP), which is a parameter that indicates the signal strength (Power) received by the user at a given frequency [23], [24]. There is also a Signal to Interference Noise Ratio (SINR) parameter, which is defined as the ratio of received signal power to interference or noise power by service consumers [25]. The bit rate or amount of data transmitted on a network in units of time is then the Throughput parameter [15]. The LTE radio access technology architecture includes several major protocols, including the Physical layer (PHY) and the PDCP[26], [27]. Header compression and decompression, encoding, integrity protection, and data transfer are the primary functions of PDCP [28]. Meanwhile, PHY layer throughput will provide a contextual mapping of the precise pace at which data will be successfully transmitted[29] . In this work, throughput is measured using both the PDCP and PHY protocols. All the parameters are analyzed and if the data is not suitable, it has to re-drive test until completed. There are several stages in the study, namely as shown in Figure 1.

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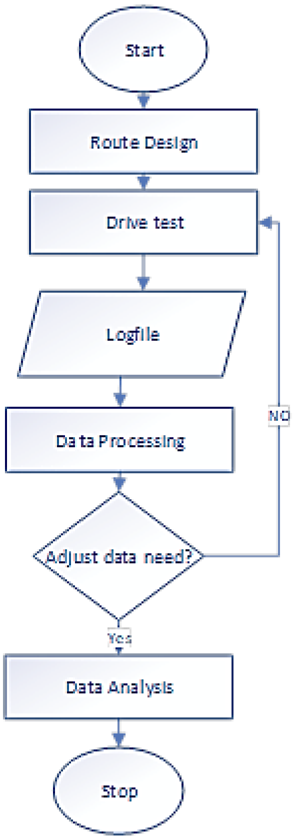


Figure 1. Diagram block of research.

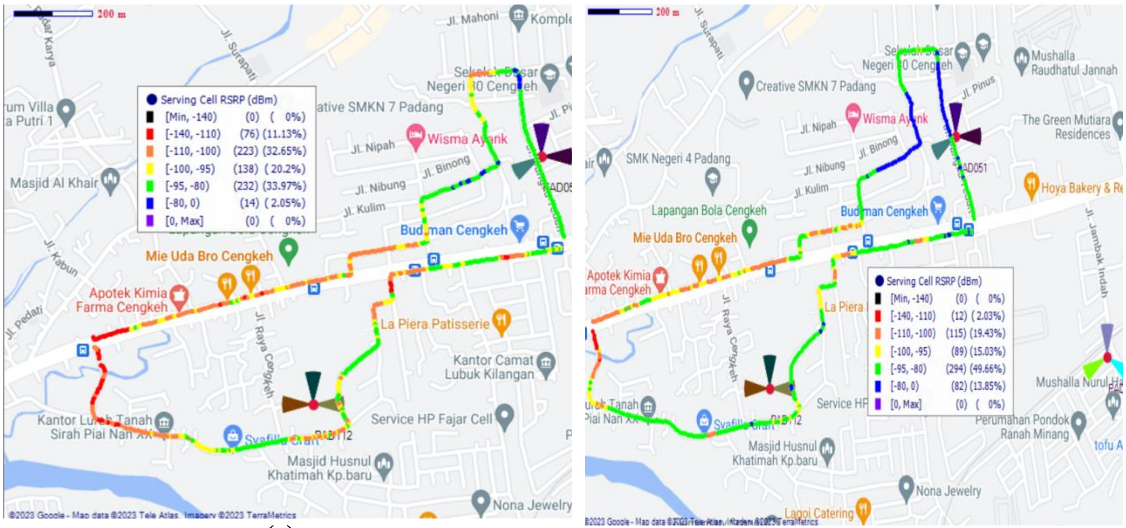
This research needs to be done by taking data in real time in the field through a drive test. For this reason, there are several things that need to be considered such as equipment preparation, route preparation, and data retrieval. In conducting a drive test there are several equipment prepared, namely Smartphones, Sim Cards, Global Positioning System, Laptops, and dongles. In conducting a drive test, it is necessary to design the route. This is necessary so that drive test activities run smoothly, so that researchers can find out how the condition of the research area. Route planning is done using Google Earth and Mapinfo Pro software to view site information info.

The logfile results obtained from the results of taking drive test data will be processed using TEMS Discovery software. Start by creating a new project and importing Data Drive Test (Logfile) on TEMS Pocket with the format "trp". The parameters analyzed are RSRP, SINR, CQI, and Throughput at the PDCP layer and PHY at downlink and uplink. These parameters are analyzed according to the range of Key Performance Indicator of Telkomsel operators.

3. Results and Analysis

3.1. Processing of downloaded data

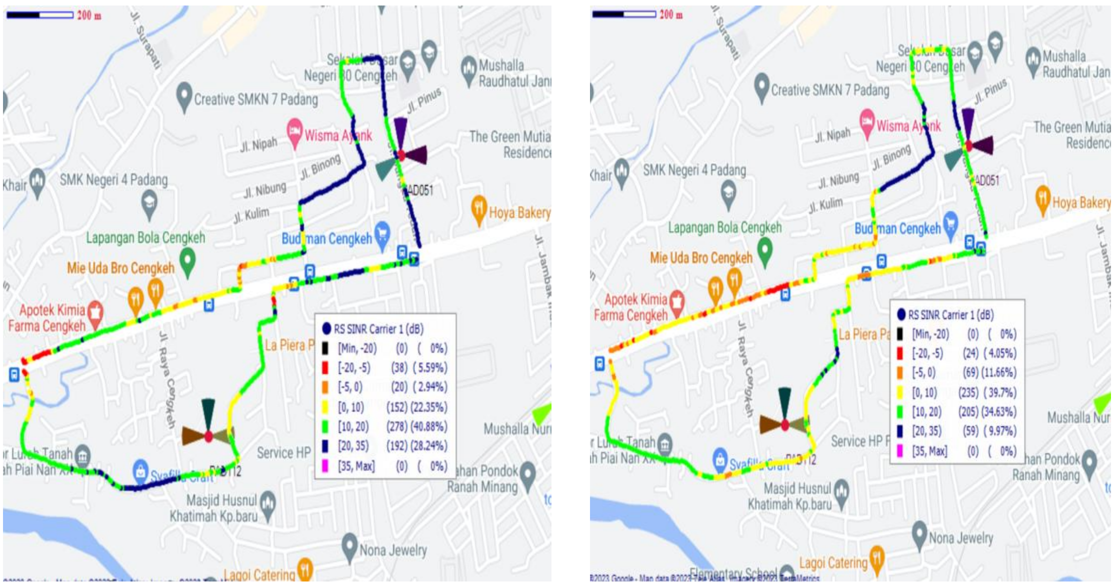
The RSRP parameter shows the power of an eNodeB. Based on Figure 2 (a) and (b), it was analyzed that the RSRP parameters of TDD and FDD technology were dominated by the very good category (-95 to -80 dBm) of 232 and 294 samples with percentages of 33.97% and 49.66%. The bad categories (-110 to -100 dBm) TDD and FDD were 223 and 115 samples with percentages of 32.65% and 19.43%. Good categories (-100 to -95 dBm) TDD and FDD were 138 and 89 samples with percentages of 20.2% and 15.03%. In the very bad category (-140 to -110 dBm) TDD and FDD were 76 and 12 samples with percentages of 11.13% and 2.03%. And the excellent category (-80 to 0 dBm) TDD and FDD are 14 and 82 samples with percentages of 1.43% and 13.85%.



(a) (b)

Figure 2. The RSRP parameter of download result (a) RSRP TDD technology and (b) RSRP FDD technology.

The SINR parameter shows the quality of the signal received by the user for services on the eNodeB. In Figure 3 (a) and (b) the SINR results of TDD and FDD technologies can be analyzed. TDD and FDD results in the very good category (10 to 20 dB) were 278 and 205 samples with percentages of 40.88% and 34.63. The excellent category (20 to 35 dB) TDD and FDD are 192 and 59 with percentages of 28.24% and 9.97%. Good category data (0 to 10 dB) TDD and FDD were 152 and 235 samples with percentages of 22.35% and 39.7%. In the very bad category (-20 to -5 dB) TDD and FDD were 38 and 24 samples with percentages of 5.59% and 4.05%. As well as the bad category (-5 to 0 dB) TDD and FDD as many as 20 and 69 samples with percentages of 2.94% and 11.66%. Based on these data, SINR TDD is dominated by the very good category, while FDD is dominated by the good category.



(a) (b)

Figure 3. The SINR parameter of download result (a) SINR of TDD technology and (b) SINR of FDD technology.

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Based on the time domain and frequency, CQI values show the quality of the communication channel. According to Table 1, the average value of CQI is 11 on TDD technology and 8 on FDD technology. Therefore, the CQI parameter for TDD technology is better than FDD technology.

Table 1. The CQI comparison of TDD and FDD download result.

CQI	CQI in TDD	CQI in FDD
Average	11	8
Minimum	3	2
Maximum	15	15

According to Table 2, the percentage of the two technologies has a varied throughput at each layer. The download findings analyse two layers: PDCP and PHY (PDSCH). In the very good category (5000-100000 kbps), PHY and PDCP TDD throughput percentage values were 95.05% and 95.14%, respectively, while FDD only attained 90.88% and 87.65. As a result, TDD outperforms FDD in terms of data throughput.

Table 2. The percentage comparison of *throughput download in* PDCP and PHY *layer*.

Category	Throughput DL (kbps)		PHY	PDCP
Very Bad	0-1500	TDD	2.7%	2.13%
		FDD	0.17%	1.02%
Bad	1500-3000	TDD	0.9%	1.06%
		FDD	2.36%	3.05%
Good	3000-5000	TDD	1.35%	1.67%
		FDD	6.59%	8.29%
Very Good	5000-100000	TDD	95.05%	95.14%
		FDD	90.88%	87.65%
Excellent	100000-200000	TDD	0%	0%
		FDD	0%	0%

3.2. Processing of uploaded data

Figures 4 (a) and (b) are the uploaded RSRP TDD and FDD parameters. The two technologies were dominated by the very good category (-95 to -80 dBm) with 348 and 304 samples, respectively, corresponding to percentages of 45.37% and 47.06%. In the bad category (-110 to -100 dBm), TDD consisted of 224 samples with a percentage of 29.2%, while FDD had 97 samples, accounting for 15.02%. In the very bad category (-140 to -110 dBm), TDD had 93 samples (12.13%), and FDD had 97 samples (15.02%). In the good category (-100 to -95 dBm), TDD comprised 91 samples (11.86%), whereas FDD included 100 samples (14.48%). Lastly, in the excellent category (-80 to 0 dBm), TDD had 11 samples (1.43%), and FDD had 135 samples, representing 20.9%.

Overall, the distribution of samples across different signal strength categories highlights a notable difference in the performance between TDD and FDD technologies. The FDD technology shows a higher concentration of samples in the excellent category, indicating better performance in terms of signal strength. Conversely, TDD has a higher proportion of samples in the bad and very bad categories, suggesting areas where signal improvement is needed. These observations can inform network optimization efforts, targeting specific areas where TDD lags behind FDD in signal quality. Additionally, the substantial presence of samples in the very good category for both technologies indicates that a significant portion of the network provides adequate signal strength, though there remains room for improvement, particularly for TDD in achieving higher signal quality similar to FDD.

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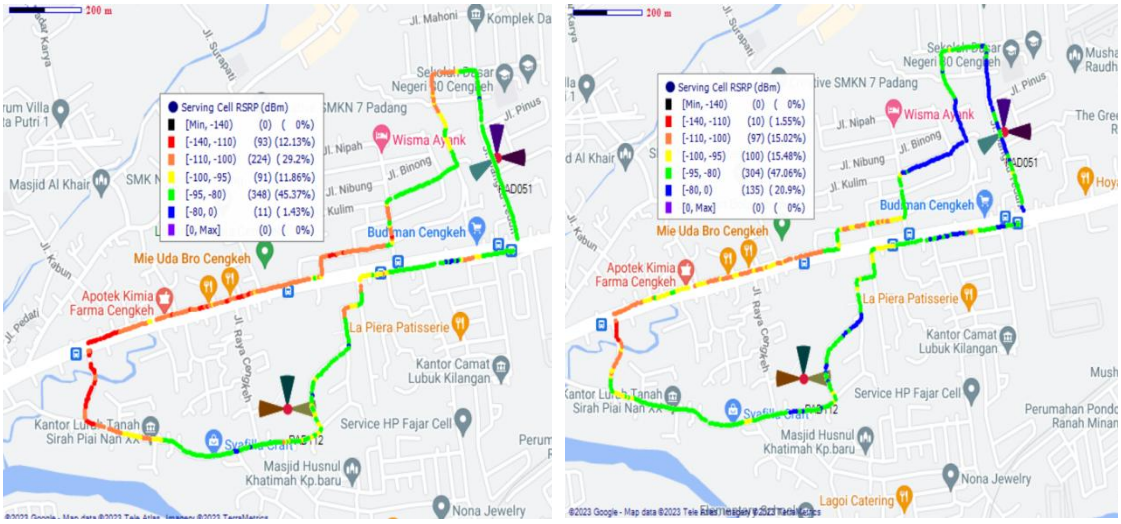
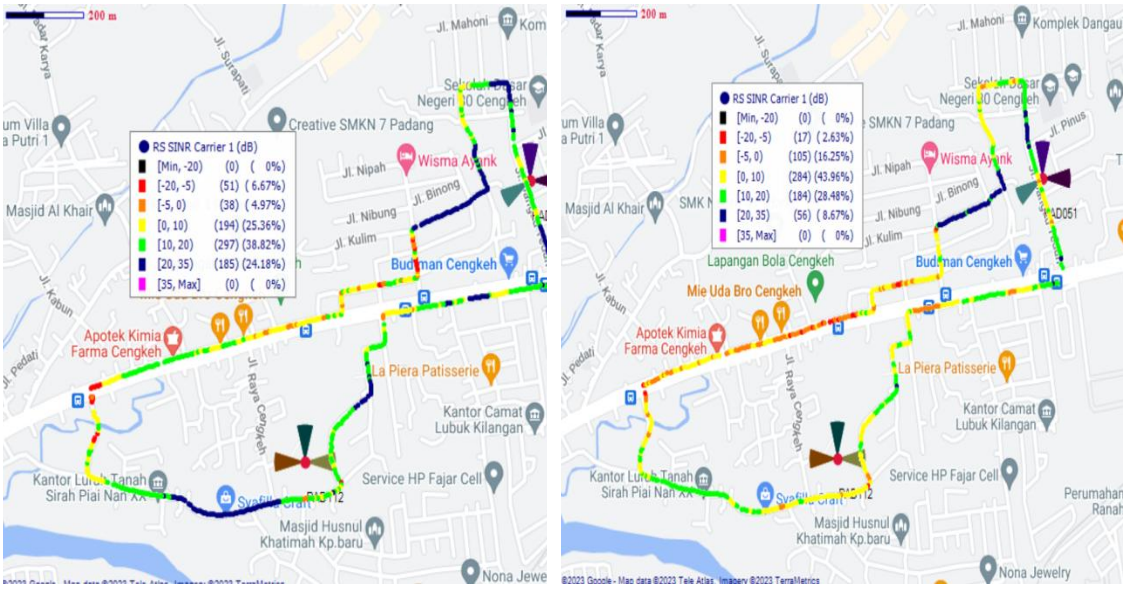


(a) (b)

Figure 4. The RSRP parameter of upload result (a) RSRP of TDD technology and (b) RSRP of FDD technology.

Figures 5 (a) and (b) show the SINR parameters of TDD and FDD technologies. In the very good category (10 to 20 dB), TDD has 297 samples with a percentage of 38.82% and FDD reaches 184 samples with a percentage of 24.48%. In the good category (0 to 10 dB), TDD has 194 samples with a percentage of 25.36% and FDD reaches 284 samples with a percentage of 43.96%. In the excellent category (20 to 35 dB), TDD consisted of 185 samples with a percentage of 24.18% and FDD reached 56 samples with a percentage of 8.67%. In the very bad category (-20 to -5 dB), TDD consisted of 51 samples with a percentage of 6.67% and FDD reached 17 samples with a percentage of 2.63%. Furthermore, in the bad category (-5 to 0 dB) TDD was 38 samples with a percentage of 4.97% and FDD reached 17 samples with a percentage of 2.63%. Thus, SINR TDD is dominated by the very good category, while FDD is good.



(a) (b)

Figure 5. The SINR parameter of download result (a) SINR of TDD technology and (b) SINR of FDD technology.

According to the uploaded findings in Table 3, the CQI data for TDD technology has an average CQI value of 10, whereas FDD has an average CQI value of 8. TDD and FDD have a minimum CQI value of 2. As a result, CQI for TDD technology is superior to FDD.

Table 3. CQI comparison of TDD and FDD upload result.

CQI	CQI in TDD	CQI in FDD
Average	10	8
Minimum	2	2
Maximum	15	15

Throughput parameters are investigated in multiple layers, including the Physical layer (PUSCH) and the PDCP layer. The throughput percentage of each layer is analysed using Table 4, which displays the differences in each layer. TDD technology upload throughput at the PHY and PDCP layers is 33.44% and 28.53%, respectively, which are in the very good category (3000 to 5000 kbps), but FDD technology is dominated by the excellent category (5000-100000 kbps) at 45.89% and 42%. As a result of uploading data, FDD technology exhibits improved throughput performance.

Table 4. Throughput comparison of upload result in PDCP and PHY layer.

Category	Throughput UL (kbps)		PHY	PDCP
Very Bad	0-1000	TDD	18.49%	26.65%
		FDD	31.79%	36.14%
Bad	1000-1500	TDD	6.93%	7.35%
		FDD	4.64%	4.48%
Good	1500-3000	TDD	20.8%	20.17%
		FDD	9.11%	9.12%
Very Good	3000-5000	TDD	33.44%	28.53%
		FDD	8.57%	8.26%
Excellent	5000-100000	TDD	20.34%	18.3%
		FDD	45.89%	42%

3.3. Comparison of download and upload results

Based on actual data, FDD technology's RSRP parameters outperform TDD technology. It has been established that the RSRP on FDD averages 91.4 dBm and -89.4 dBm for both download and upload data outcomes. Meanwhile, the RSRP on TDD was -98.2 dBm and -97.6 dBm, respectively. This is influenced by the usage of FDD 2100 MHz technology, which has a lower frequency than TDD 2300 MHz technology. Because higher frequencies produce shorter waves, they enhance the occurrence of multipath fading. As a result, TDD technology has lower signal strength in this area.

TDD technology outperforms FDD technology in SINR parameters. According to the results, the average SINR TDD for download and upload was 13.4 dB and 12.1 dB, respectively, while FDD was 8.9 dB and 7.4 dB. This is influenced by CQI in TDD technology, which is also better, with an average CQI of 11 and 8 in download and upload results, respectively, compared to 8 in FDD. The better the modulation, the higher the CQI value, and vice versa.

The download and upload results show a disparity in the throughput of the PDCP and PHY layers. The average download and upload throughput values for TDD and FDD technologies are shown in Table 5. TDD technology's average throughput values for downloading the PDCP and PHY (PDSCH) layers are 22457.3 kbps and 26842.3 kbps, respectively, while FDD technology reaches 18687.7 kbps and 21790.6 kbps. The average throughput values of PDCP and TDD technology PHY in the upload results are 2832.34 kbps and 3175.4 kbps, respectively, while FDD is 3733.12 kbps and 4425.9 kbps. It can be seen that the PDCP throughput value is lower than the PHY throughput value. This is because the two layers have different responsibilities. The PDCP is responsible for ensuring that data is correctly delivered by compressing and decompressing header data, as well as sorting and interpreting the data sent, using various protocols. This adds extra overhead to data packets, resulting in a reduced throughput size at this layer. Because resources must be assigned in advance to carry out the encryption function, the complexity of encryption at the PDCP layer demands more time and can reduce throughput. The PHY throughput shows control over coding or decoding, modulation/demodulation, and multi-antenna mapping, as well as a contextual mapping of the exact speed at which data is effectively delivered. The physical layer also includes a header, which contains the control and identifying information required for sending data through the network. The addition of headers may result in additional transmission overhead. The overhead at the physical layer, on the other hand, contains the least overhead required to perform the basic operations of transferring data through the transmission channel. Overhead at this layer differs from overhead at the layer above, such as the PDCP layer, which incorporates more complex compression, encryption, and other features. Furthermore, the throughput at the PHY layer is the effective speed at which physical data can be conveyed across the transmission media, hence the throughput at this layer is affected by modulation in actual real-world settings such as interference hurdles.

Table 5. Comparison of average throughput in TDD and FDD.

Throughput Parameter		TDD Technology		FDD Technology	
		Download	Upload	Download	Upload
Mean Throughput (kbps)	PDCP	22457.3	2832.34	18687.7	3733.12
	PHY	26842.3	3175.4	21790.6	4425.9

The difference between download and upload throughput is also determined by the downlink and uplink technology configurations. TDD technology employs type 5, which provides for an 8:1 ratio of downlink to uplink use, implying that the downlink channel is superior to the uplink. This is also influenced by user traffic requirements. Currently, people prefer to access the internet through the downlink channel. As a result, using this form of arrangement is the best option. Unlike FDD, which has a different frequency for each downlink and uplink channel. This can effectively optimise both channels. As a result, the upload throughput value on TDD technology is lower than on FDD technology.

4. Conclusion

This study was successful in comparing download and upload speeds on 4G LTE technology, specifically TDD at 2300 MHz and FDD at 2100 MHz. According to the research, the RSRP results on FDD demonstrate better performance. This is because the frequency used on FDD is lower than the frequency used on TDD, resulting in a bigger coverage area in each eNodeB sector. The SINR parameter on TDD then performs better because of the usage of better modulation and channels in this technology. TDD technology's downlink and uplink channel capacities are affected by the configuration mode design used due to the use of one frequency for both channels, while FDD uses two different frequencies for the two channels. In this study, TDD technology uses a type 5 configuration with a downlink and uplink ratio of 8:1. Therefore, the download throughput (PDCP and PDSCH) of TDD technology is higher. The configuration type used in this technology supports more downlink capacity, whereas the upload throughput (PDCP and PUSCH) of FDD technology is higher because this technology balances the downlink and uplink channels. Thus, there are variances between TDD and FDD download and upload results, and based on the study of the data, these parameters have an average value in the very good category, and have satisfied Telkomsel's KPI standards.

References

[1] M. Ulema, *Fundamentals of public Safety Metworks and Critical Communication System*, 10th ed. New York: The Institute of Electrical and Electronics Engineers, Inc., 2019.

[2] Y. Saragih, R. Satrio Hadikusuma, and A. Elisabet S, “Evaluation of cellular network performance involving the LTE 1800 band and LTE 2100 band using the drive test method,” *JURNAL INFOTEL*, vol. 14, no. 4, Nov. 2022, doi: 10.20895/infotel.v14i4.833.

[3] C. Gunturu and S. Valluri, “A new complexity reduction scheme in selective mapping-based visible light communication direct current-biased optical orthogonal frequency division

multiplexing systems," *IET Optoelectronics*, vol. 16, no. 5, pp. 207–217, Oct. 2022, doi: 10.1049/ote2.12074.
[4] R. Manda, A. Kumar, and R. Gowri, "Optimal Filter Length Selection for Universal Filtered Multicarrier Systems," *International Journal of Engineering*, vol. 36, no. 07, pp. 1322–1330, 2023, doi: 10.5829/ije.2023.36.07a.13.
[5] S. P. M. U. M. W. Sheeba P, "Equalization Techniques for SC-FDMA Systems Under Radio Imbalances at Both Transmitter and Receiver," *Res Sq*, Jul. 2022.
[6] T. McKerahan, "Performance Analysis of Adaptive Modulation and Coding Over AWGN Channel in an OFDM System," *International Journal of Research in Engineering, Science and Management*, vol. 6, no. 5, pp. 72–78, 2023, [Online]. Available: https://www.ijresm.com
[7] T. Kebede, Y. Wondie, J. Steinbrunn, H. B. Kassa, and K. T. Kornegay, "Multi-Carrier Waveforms and Multiple Access Strategies in Wireless Networks: Performance, Applications, and Challenges," *IEEE Access*, vol. 10, pp. 21120–21140, 2022, doi: 10.1109/ACCESS.2022.3151360.
[8] H. Adhami, M. Alja'afreh, M. Hoda, J. Zhao, Y. Zhou, and A. El Saddik, "Suitability of SDN and MEC to facilitate digital twin communication over LTE-A," *Digital Communications and Networks*, Jun. 2023, doi: 10.1016/j.dcan.2023.05.008.
[9] A. Saghir, B. A. Bhatti, and S. J. Yawar, "Analysis of LTE-Advanced Uplink System for the Effect of Carrier Frequency Offset and Ratio of Peak to Average Power," *Journal of Xi'an Shiyou University,Natural Science Edition*, vol. 18, no. 8, pp. 245–252, Aug. 2022.
[10] R. Saadia, "Single Carrier-Frequency Division Multiple Access Radar: Waveform Design and Analysis," *IEEEAccess*, vol. 8, pp. 35742–35751, Feb. 2020.
[11] T. Javornik, A. Hrovat, and A. Švigelj, "Radio technologies for environment-aware wireless communications,"Nov. 2022, [Online]. Available: http://arxiv.org/abs/2211.16850
[12] S. S. Suliman, "Capacity Performance Analysis Of NOMA For 5G Network," Sudan, Dec. 2022.
[13] N. N. Sirhan and M. M. Ramon, "LTE CELLULAR NETWORKS PACKET SCHEDULING ALGORITHMS IN DOWNLINK AND UPLINK TRANSMISSION: A SURVEY," *International Journal of Wireless & mobile Networks (IJWMN)*, vol. 14, no. 2, pp. 1–15, Apr. 2022.
[14] R. Imzhagi, H. Putri, and H. D. Priyanto, "Comparative Analysis of TDD Frame Structure Technology LTE-Advanced (A Case Study in Cibitung Area Indonesia) ," *Journal of Hunan University*, vol. 49, no. 1, pp. 141–147, Jan. 2022.
[15] D. Chandra, S. Yusnita, and D. Ba. Sitepu, "LTE Network Area Coverage on FDD and TDD Technology," *International Journal of Advanced Science Computing and Engineering*, vol. 2, no. 1, pp. 21–33, Apr. 2020.
[16] P. Harahap, F. I. Pasaribu, and C. A. Siregar, "Network Quality Comparison 4g LTE X And Y in Campus UMSU," *J Phys Conf Ser*, vol. 1858, no. 1, p. 012010, Apr. 2021, doi: 10.1088/1742-6596/1858/1/012010.
[17] E. M. Woldamanuel and F. D. Diba, "Enhanced adaptive code modulation for rainfall fade mitigation in Ethiopia," *EURASIP J Wirel Commun Netw*, vol. 2022, no. 1, Dec. 2022, doi: 10.1186/s13638-021-02085-0.
[18] A. Balieiro, K. Dias, and P. Guarda, "Addressing the CQI feedback delay in 5G/6G networks via machine learning and evolutionary computing," *Intelligent and Converged Networks*, vol. 3, no. 3, pp. 271–281, Dec. 2022, doi: 10.23919/icn.2022.0012.
[19] D. Chandra, F. Aditia Rahmat, S. Aulia, and A. Febrian Kasmar, "Effect of Modulation on Throughput of 4G LTE Network Frequency 1800 MHz," 2023.
[20] F. F. Al Azzawi, Z. F. Al Azzawi, S. F. Al Azzawi, and F. A. Abid, "Reference measurement channel RMC parameters of LTE downlink waveforms," in *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, Aug. 2020. doi: 10.1088/1757-899X/881/1/012107.

[21] Z. Shakir, A. Y. Mjhool, A. Al-Thaedan, A. Al-Sabbagh, and R. Alsabah, "Key performance indicators analysis for 4 G-LTE cellular networks based on real measurements," *International Journal of Information Technology (Singapore)*, Mar. 2023, doi: 10.1007/s41870-023-01210-0.

[22] D. D. Michel and K. I. Basile, "Web based 4G Drive Tests Post Processing Software for Educational and Enterprise Purpose," *Advances in Image and Video Processing*, vol. 10, no. 3, May 2022, doi: 10.14738/aivp.103.12348.

[23] A. Bellary, K. Kandasamy, and P. H. Rao, "Analysis of Wave Propagation Models with Radio Network Planning Using Dual Polarized MIMO Antenna for 5G Base Station Applications," *IEEE Access*, vol. 10, pp. 29183–29193, 2022, doi: 10.1109/ACCESS.2022.3158948.

[24] P. Rahmawati, A. Hikmaturokhman, K. Ni'amah, and M. I. Nashiruddin, "LoRaWAN Network Planning at Frequency 920-923 MHz for Electric Smart Meter: Study Case in Indonesia Industrial Estate," *Journal of Communications*, vol. 17, no. 3, pp. 222–229, Mar. 2022, doi: 10.12720/jcm.17.3.222-229.

[25] J. Viana *et al.*, "A Convolutional Attention Based Deep Learning Solution for 5G UAV Network Attack Recognition over Fading Channels and Interference," in *IEEE Vehicular Technology Conference*, Institute of Electrical and Electronics Engineers Inc., 2022. doi: 10.1109/VTC2022-Fall57202.2022.10012726.

[26] E. Dahlman, S. Parkvall, and J. Sköld, *4G, LTE-advanced pro and the road to 5G*, Third edition. Elseviert Ltd, 2016.

[27] A. L. Imoize, F. Udeji, J. Isabona, and C. C. Lee, "Optimizing the Quality of Service of Mobile Broadband Networks for a Dense Urban Environment," *Future Internet*, vol. 15, no. 5, May 2023, doi: 10.3390/fi15050181.

[28] D. Hasselquist, C. Lindström, N. Korzhitskii, N. Carlsson, and A. Gurtov, "QUIC Throughput and Fairness over Dual Connectivity," *Computer Networks*, vol. 219, Dec. 2022, doi: 10.1016/j.comnet.2022.109431.

[29] I. Joseph, O. Ituabhor, J. Timothy zhimwang, and R. Ikechi, "Achievable Throughput over Mobile Broadband Network Protocol Layers: Practical Measurements and Performance Analysis," *Int. J. Advanced Networking and Applications* , vol. 13, no. 4, pp. 5037–5044, 2022.