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Article

Design and Evaluation of mmWave MIMO Networks Using 28 and 60 GHz in Urban Areas

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Abstract. A new alternative network is critical since cellular users are increasing year after year and network capacity is becoming insufficient. Currently, network design prioritizes not only performance but also energy efficiency. The MIMO system has existed for a long time and has been shown to improve system performance. A mmWave technology is currently one of the 5G enabling technologies that use high frequencies to enable speeds of up to 1 Gbps while maintaining high capacity and low latency. Thus, the combination of mmWave technology and MIMO systems is one of the challenges for implementing 5G technology with high performance and energy efficiency in urban areas. This paper, therefore, designs and evaluates the mmWave MIMO network using 28 and 60 GHz frequencies in urban areas, especially in Banda Aceh city. Then, this paper analyzes the designed network performance by considering coverage area, SINR, throughput, and energy efficiency. The designed mmWave MIMO system uses different antennas: 4, 8, 16, and 32. Simulation results indicate that the mmWave MIMO 28 GHz network has a larger coverage area, higher SINR, and more energy efficiency than the mmWave MIMO 60 GHz network. The highest energy efficiency is achieved in the network using a 16-antenna. On the other hand, the throughput of a mmWave MIMO 28 GHz network is lower than that of a mmWave MIMO 60 GHz network. The mmWave MIMO 28 GHz network has demonstrated advantages that make it ideal for use in urban areas, particularly in Banda Aceh.

Keywords: mmWave, MIMO, 5G technology, evaluation, performance.

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1. Introduction

The development of digital communication and wireless networks is accelerating, as evidenced by the rise in data transfer rates and the number of users. This decreases the available bandwidth, thereby increasing the required capacity to implement a reliable communication system. One of the most recent digital communication technologies, 5G technology is capable of enhancing network traffic lanes by making huge capacity available. Some of the most widely used 5G support technologies are Multiple Input Multiple Output (MIMO), millimeter-wave (mmWave), and device-to-device (D2D) [1].

MIMO technology is a refined version of a wireless spatial diversity system that employs a single antenna known as Single-Input Single-Output (SISO). MIMO technology operates at least two antennas in the transmitter and receiver. When more antennas are utilized, efficacy and diversity gain are enhanced. In addition, the advantages of MIMO technology can increase both link capacity and system capacity, as well as system reliability, by reducing mutual coupling induced by fading [2], [3]. MmWave technology is one of the 5G supporting technologies that has a wavelength of 1-10 mm and operates at an Extremely High Frequency (EHF) of 30-300 GHz with large bandwidth. The mmWave 5G network is, therefore, a potential remedy for accommodating future bandwidth demands [4], [5].

MIMO and mmWave technologies can be combined in order to meet the requirements of future 5G networks [6], [7]. The combination of the two technologies is known as mmWave MIMO, and it provides a wide range of advantages, including (a) the availability of multiplexing and array amplification due to a large number of transmitting and receiving antennas; (b) extreme data rates due to the large bandwidth at millimeter frequencies; and (c) interference reduction due to narrow beamforming. mmWave MIMO has the potential to increase user throughput, cellular network capacity, spectral efficiency, and energy efficiency [8] by utilizing this combination of the large bandwidth available in the mmWave frequency band and the high multiplexing advantages of massive antenna arrays. One of the applications of mmWave MIMO is in HetNet 5G wireless, the next-generation cellular network with the benefits of extraordinary infrastructure densification, a large new bandwidth, and an enormous number of antennas. Therefore, this combination affords the chance to support a multitude of high-speed services for future applications requiring large bandwidths [9]. However, the higher attenuation of mmWave waves is still caused by the use of high frequencies.

Recently, 5G technology applications in the industry have also used a frequency spectrum close to mmWave, such as 28 GHz, which has many of the same operating characteristics as mmWave frequencies [10], [11]. Together with 39 GHz and higher frequencies, these frequency bands are referred to as millimeter waves [12]. mmWave attenuation studies at 28 GHz have revealed that mmWave waves prefer to permeate materials such as polystyrene or pass through without reflection. However, different reflections were discovered, ranging from wood and wall materials to materials such as colored glass and bricks that create strong reflections, resulting in increased attenuation. Ullah et al. [13] proposed one of the developments of mmWave MIMO technology in the range between 57-63 GHz by creating a ground plane antenna array based on an electromagnetic bandgap (EBG) structure that can give a significant reduction in coupling. According to the study's findings, numerous types of EBG materials and architectures that can greatly improve performance are found in the MIMO system operating in the 60 GHz band. Whereas most MIMO system performance measures are based on the total gain of MIMO components and connections between antenna ports, utilizing metamaterial or the EBG band gap can lessen the connection between closely spaced antennas in the 60 GHz mmWave band. Furthermore, the issue of increasing user numbers and the necessity for high data throughput on 5G networks can be addressed using a combination of D2D and mmWave. The incorporation of mmWave communication in D2D has been shown to improve the performance of a pico cell network throughput in the 60 GHz band by up to 2.3 times over conventional D2D technology [1].

In order to successfully implement 5G wireless communications, it is essential not only to design the overall system but also to evaluate its performance. This paper, therefore, proposes the design and evaluation of a 5G communication system based on MIMO and mmWave technologies at 28 and 60 GHz. It seeks to increase the energy efficiency and performance of the communication system. For the case study, the network is modeled as an urban area in Banda Aceh, Indonesia. The network design considers the various MIMO antennas, network parameters, coverage parameters, and power consumption. In addition, the designed mmWave MIMO 5G communication system was evaluated utilizing a variety of performance metrics, including coverage, signal-to-interference-plus-noise ratio (SINR), throughput, and energy economy. Based on simulation results, we evaluate the viability of mmWave MIMO 28 and 60 GHz deployment in urban areas, particularly in Banda Aceh. The main contribution of this paper can be summarized as follows:

a. We design a mmWave MIMO network using 28 and 60 GHz in Banda Aceh city, as an urban area.
b. We evaluate the performance and energy efficiency of the designed mmWave MIMO network using the 28 and 60 GHz in Banda Aceh city.

2. Network Design

The mmWave MIMO 5G is an emerging technology that combines the potentially large mmWave bandwidth availability and the high gain of MIMO antenna arrays [14], [15]. Using mmWave-MIMO in the HetNet domain, the next generation of cellular networks can be proposed to take advantage of extreme infrastructure densification, vast quantities of new bandwidth, and a significant increase in the number of antennas. In addition, this combination enables the support of numerous high-speed services for applications requiring extensive bandwidth. Wide bandwidth availability and high spectrum efficiency make mmWave MIMO a promising option for future 5G cellular networks seeking to significantly increase overall system throughput. mmWave communication has the disadvantage of a high path loss during transmission. In general, mmWave communication systems reduce path loss with directional beamforming and multiple antenna arrays.

To take advantage of the opportunity to integrate mmWave MIMO technology, a variety of communication theory and engineering obstacles must be surmounted. In addition, challenges include research issues and future directions of mmWave MIMO as an up-and-coming technology today. In spite of this, mmWave MIMO technology can provide a vital solution to many future technical communication challenges, particularly for 5G HetNet networks, and can integrate effectively with existing network and access technologies. Moreover, deploying multiple antennas at the MIMO transmitter and/or receiver can substantially improve the spectral and energy efficiency of a wireless network [16].

This research begins with placing macro site positions according to urban areas. The macro BTS's beam direction uses angles of 30°, 150°, and 270°. Using beamforming techniques, the beam received by multiple microsites predicts the amount of power received at each microsite. Finally, the free space propagation model predicts the received signal strength for each microsite to optimize directivity.

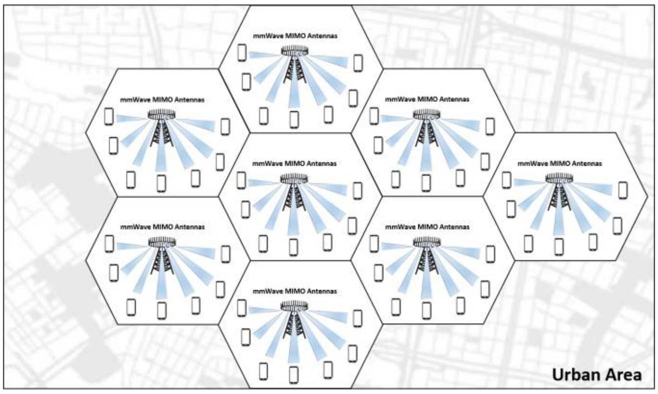


Fig. 1. Network design model for mmWave MIMO in an urban area.

Figure 1 depicts the designed network architecture for mmWave MIMO in an urban area. The designed network is simulated using Matlab in Banda Aceh city for the case study of an urban area. Each BTS employs mmWave MIMO antennas for the 28 and 60 GHz frequencies and serves a large number of user equipment (UE). The MIMO antennas used on the Tx and Rx are 2×2 (4 antennas), 2×4 (8 antennas), 4×4 (16 antennas), and 4×8 (32 antennas) on the mmWave MIMO 28 and 60 GHz, respectively. Several factors must be considered during the design process, such as the path loss that impacts signal coverage [17]. In addition, the high frequencies utilized by the mmWave MIMO network will have an impact on the coverage of the designed model. The overall parameters considered in network design are listed in Table 1.

Table 1. Network parameters.

Item	Remarks
Operational frequencies	28 and 60 GHz
Environment	outdoor
Communication method	mmWave MIMO
Transmit power	44 dBm
Noise type	Noise thermal
Antenna height	10 m
UE height	1.5 m
Temperature	23^0C

The considered parameters to measure the coverage of the mmWave MIMO network with operating frequencies of 28 and 60 GHz are shown in Table 2 [17].

Table 2. Coverage parameters.

Item	28 GHz	60 GHz
Bandwidth total	2 GHz	7 GHz
UE bandwidth channel	20 MHz	20 MHz
Receiver bandwidth channel	50 MHz	50 MHz
Feed loss of array antennas	2 dB	2 dB
Transmit power at BS	44 dBm	44 dBm
Antenna gain at transmitter and receiver	10 dBi	10 dBi
Number of MIMO antennas at micro-site	4, 8, 16 and 32	4, 8, 16 and 32
Macro-site antenna height	25 m	25 m
Receiver antenna height	1.5 m	1.5 m

In the designed network, the power consumption of the base station (BS) is calculated to analyze the energy efficiency of the mmWave MIMO system at different frequencies [18]. The power consumption of the BS is shown in Table 3.

Table 3. Power consumption at the base station.

Parameter	Description	Value
P_{trans}	Transceiver power at antenna	1.5 W
η	The power efficiency of the amplifier	50%
P_{bhl}	Backhaul power	10 W
P_{cool}	Power at cooler system	200 W
P_{rect}	Rectifier power	50 W
P_{dsp}	Processing signal power at antenna	1 W

3. Performance Analysis

3.1. Coverage

Coverage of the mmWave MIMO network is highly sensitive to system performance and reveals the distribution density level. Nonetheless, the millimeter-wave signal propagates poorly in the non-line-of-sight (NLOS) region [18]. Coverage is limited by wave propagation through walls and furniture. Transmission distance indoors is 10 m and outdoors 100 m. The communication path through a vacuum will be a limitation at high frequencies, i.e., 60 GHz. For this reason, one solution is to integrate the existing 5 GHz network with the 60 GHz band [19]. This study uses the MATLAB application's phased array system and antenna toolbox to calculate the mmWave MIMO network coverage at a frequency of 28 and 60 GHz.

Network coverage is affected by network reception and losses. Receive power is measured from the user's receiving base station via air propagation. The received power is calculated based on the transmit power (P_{tx}) minus the total power attenuation (L_{total}) as follows [20]:

$$P_{rx} = P_{tx} - L_{\text{total}} \quad (1)$$

where P_{rx} is received power (dBm), P_{tx} is transmitted power (dBm), and L_{total} is the total of attenuation power (dBm). L_{total} is calculated by [20]

$$L_{\text{total}} = L_{fs} + L_b - G_{Tx} - G_{Rx} + PL(d) \quad (2)$$

where L_{fs} is free space loss (dB), L_b is installation losses (dB), G_{Tx} is base station antenna gain (dB), G_{Rx} is receiver antenna gain (dB), and $PL(d)$ is path loss (Km).

Path loss (PL) is due to NLOS between two communication antennas separated by a distance d in kilometers (km) and operating at a frequency f in GHz. X_σ is a zero mean Gaussian random variable with a standard deviation in dB, which is obtained as [21]

$$PL(d) = PL(d_0) + 10n\, log_{10}\left(\frac{d}{(d_0)}\right) + X_\sigma \quad (3)$$

where the $PL(d_0)$ is obtained from the close-in attenuation of free space using the reference distance $d_0 = 1$ m, then

$$PL(d_0) = 10\, log_{10}(\frac{4\pi d_0}{\lambda})^2 \quad (4)$$

where λ is the wavelength used in the network. The larger the wavelength, the smaller the frequency used and the smaller the path attenuation.

3.2. SINR

Signal-to-interference plus noise ratio (SINR) compares the received signal power and the power of the interference signal that has been added to the noise signal. Interference is very important to consider in designing and analyzing wireless network performance. Interference occurs when the desired signal is combined with another unwanted signal sent from another source in the same frequency, space, or time slot.

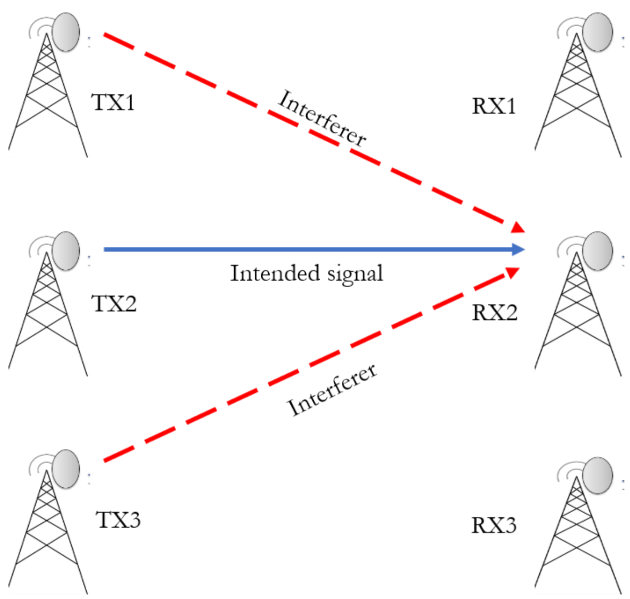


Fig. 2. SINR calculation model.

Figure 2 shows the SINR calculation model with a pair of transmitters and intended receivers denoted by *i*. Transmitters TX1 and TX2 act as interfering potentials for transmission between TX i and RX i 's intended receiver. The SINR can be written as [22]

$$SINR_i = \frac{S}{\sum i_k + n} \quad (5)$$

where $SINR_i$ is the SINR at antenna *i* (dB), S is signal power (dBm), i_k is interference power from interferer k (dBm), n is noise power (dBm). Signal power and interference power of interferer k are indeterminate variables that are influenced by various factors such as transmit power, interference management, antenna pattern, and beamforming technique used. Therefore, the SINR can be further written as [22]

$$SINR_i = \frac{P_i g_i^{Tx} g_i^{Rx} g_i^{Ch}}{\sum_{k\epsilon\Im} P_k g_k^{Tx} g_k^{Rx} g_k^{Ch} + n} \tag{6}$$

where all interference transmitters, excluding the transmitter, referred to are denoted by $\Im$, P_i is transmitted power by TXi, g_i^{Ch} is channel gain between TXi and RXi, g_i^{Tx} is antenna gain at TXi, g_i^{Rx} is antenna gain at RXi, and n is white Gaussian noise power.

3.3. Throughput

Throughput can be achieved almost equal to bandwidth, but power consumption increases linearly due to the conversion of analog to digital converters on power circuits with bandwidth. The high capacity of the 5G communication system is contingent on the mmWave band's low power transmission and low SINR ratio [23]. Data rates continue to increase from 1 Mbps in the first generation to 600 Mbps with MIMO 802.11n products. The IEEE 802.11n working group established the very high throughput study group (VHT SG) to investigate multi-gigabit link-throughput technologies. Using environmental models, including WLAN, such as sync-and-go, downloading videos or images from a camera necessitates a greater throughput as the quality and resolution increase [24]. The throughput capacity can be calculated by

$$C = B.log_2[\det(I_m + SINR \times H \times H^*)] \tag{7}$$

where B is bandwidth (Hz), H is channel gain, H^* is transpose matrix of H, and I_m is the identity matrix. In this case, the MIMO system is considered a set of parallel SISO systems. Therefore, the H channel matrix's singular value decomposition (SVD) produces a SISO independent channel.

3.4. Energy Efficiency

It also has an effect on the environment in the field of cellular communication systems, as energy consumption rises over time. As a branch of the industrial sector, mobile communications networks are responsible for approximately 0.2% of global emissions, representing a minor portion of the current total carbon footprint of Information and Communication Technologies (ICTs). With the rising demand for communication services in developing nations, however, significant challenges regarding the energy needs of cellular radio networks are anticipated to emerge in the future. In order to reduce global emissions, it is necessary to calculate energy efficiency when designing cellular communication systems [18]. Cellular communication systems of today typically utilize an outdoor base station (BS) in the cell's center to communicate with cell phone users, regardless of whether they reside indoors or outdoors. For indoor users to communicate with an outdoor BS, the signal must pass through the building's walls, resulting in extremely high penetration loss and a substantial decrease in data rate, spectral efficiency, and energy efficiency of wireless transmission.

At mmWave frequencies, energy efficiency will be a critical factor because 5G cellular architecture may separate outdoor and indoor scenarios. Therefore, designing the mmWave network for frequencies between 28 and 60 GHz becomes one of the analyzed variables. Energy efficiency (EE) can be calculated by [19]

$$\text{EE} = \frac{A.R.U}{P_{EL}} \tag{8}$$

where A is the coverage area by BS (Km^2), U is the number of users in the network, R is the bit rate based on the base station (Mbps), and P_{EL} is power consumption by the base station. Power consumption at the base station affects the energy efficiency; the smaller the power consumption of the base station, the greater the energy efficiency. The power consumption can be calculated by [18]

$$P_{EL} = N_{ant} \cdot (P_{trans} + P_{dsp} + \eta \cdot P_{amp}) + P_{rect} + P_{cool} + P_{bhl} \tag{9}$$

where Nant is the number of the BS antenna element, Ptrans is RF transceiver power (W), Pdsp is the power consumption of DSP unit (W), η is amplifier efficiency, Pamp is amplifier power (W), Prect is rectifier power (W), Pcool is AC power (W), Pbhl is link backhaul power (W), and P_{EL} is digital beamforming power (W).

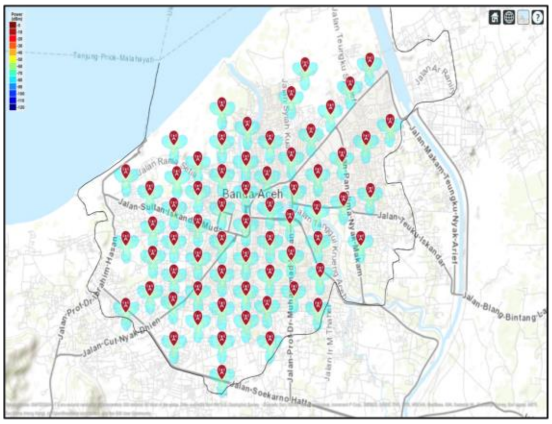
4. Results and Discussions

4.1. Coverage

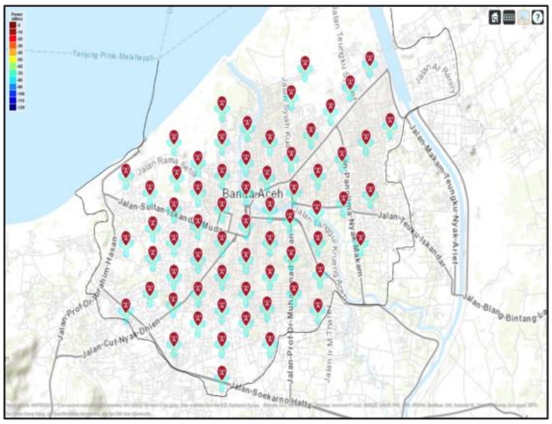
Coverage is one of the most crucial aspects of mmWave MIMO network design in order to guarantee functionality. In a mmWave MIMO network, transmit power must be simulated to measure SINR at receivers in order to analyze coverage. The Signal-to-Interference-and-Noise-Ratio (SINR) is subsequently an essential factor in determining network coverage. This network coverage is simulated using MATLAB in this paper. In the mmWave MIMO network, coverage is initially calculated based on the receiving capacity at a range of 0 to 350 m between the receiving device and the base station. The results of the simulation indicate that the received power from the mmWave MIMO network emission pattern is 44 dBm. This reception is affected by several factors, including signal attenuation due to atmospheric attenuation, foliage attenuation, equipment attenuation, and precipitation attenuation. The simulation also takes antenna gain into account so that the received power lies between -60 dBm and -84 dBm. Figure 3 depicts the signal strength simulation results for the coverage of the mmWave 28 and 60 GHz networks with eight antennas.

This coverage or signal intensity is the received power at a particular location or region.

Figure 3 (a) is the simulation result of strong signal coverage at a frequency of 28 GHz. The best-received power quality is - 5 dBm, and the lowest received value is - 120 dBm. The sensitivity of the receiver's remaining receiving power is -100 dBm. To avoid blank regions, there are 65 simulated base stations, and the receiving power is below the threshold of -100 dBm. When the number of base stations exceeds 65, the received power will increase, but the energy efficiency will decrease due to the high power consumption of the base station. As a result, 65 base stations are utilized because they are adequate to cover the entire desired coverage area and have optimal energy efficiency. Figure 3 (b) shows the results of strong signal coverage for the mmWave MIMO frequency at 60 GHz. The simulation results get the received signal power at -80 dBm.



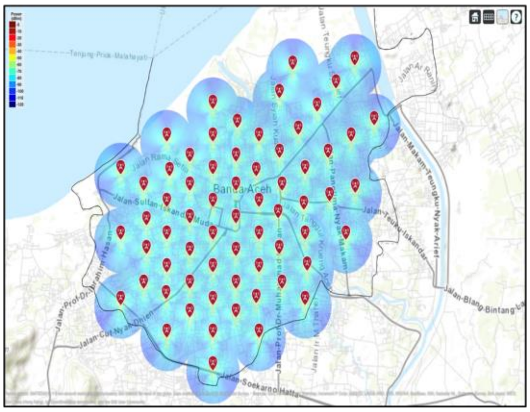
(a)



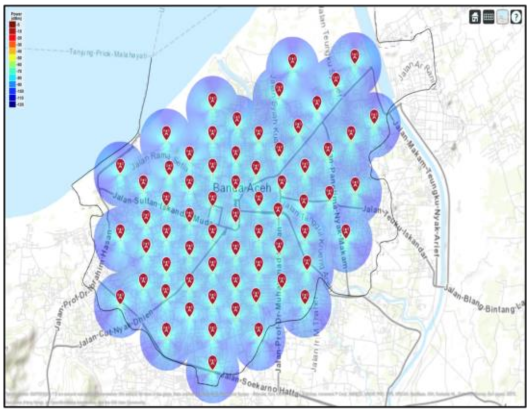
(b)

Fig. 3. Strong signal coverage with 8-antenna for (a) mmWave 28 GHz and (b) mmWave 60 GHz.

Figure 4 displays the simulation results for limited signal coverage of the mmWave MIMO network at 28 GHz (Fig. 4 (a)) and 60 GHz (Fig. 4 (b)) for each frequency. In Fig. 4 (a), the 8-antenna result for signal quality is -80 dBm. However, coverage is relatively excellent due to the wider receiving power range of the light blue color. Figure 4 (b) displays in blue a signal quality of -120 dBm. Nevertheless, the signal coverage is less than that of a 28 GHz signal.

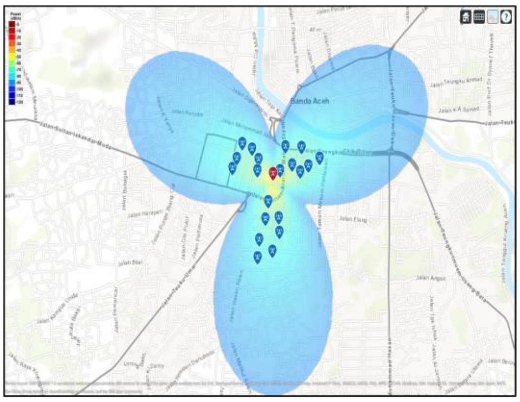


(a)

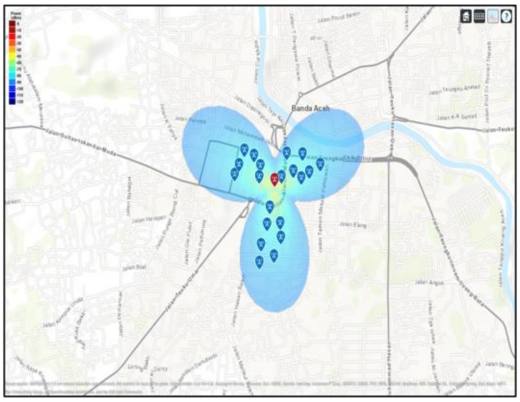


(b)

Fig. 4. Weak signal coverage with 8-antenna for (a) mmWave 28 GHz and (b) mmWave 60 GHz.



(a)



(b)

Fig. 5. Coverage with 8-antenna for 20 users: (a) mmWave 28 GHz and (b) mmWave 60 GHz.

We can see a clearer coverage area in Fig. 5, with the number of users in the figure as many as 20 UE at each BS. It shows the widest coverage at a frequency of 28 GHz with 8-antenna (Fig. 5 (a)) and the smallest coverage at 60 GHz with 8-antenna (Fig. 5 (b)). Thus, it can be concluded that 28 GHz has a larger reception area and greater coverage than 60 GHz.

Based on the coverage simulation results for a BS with 20 UE, Fig. 6 depicts the coverage based on the number of antennas used in the BS for each mmWave MIMO 28 and 60 GHz. The number of antennas used impacts the network's coverage area; the more antennas used, the larger the network's coverage area. As a consequence, both mmWave MIMO 28 GHz and mmWave MIMO 60 GHz networks will have expanded coverage. For all simulated antennas, the coverage of the mmWave MIMO 28 GHz network is greater than that of the mmWave MIMO 60 GHz network.

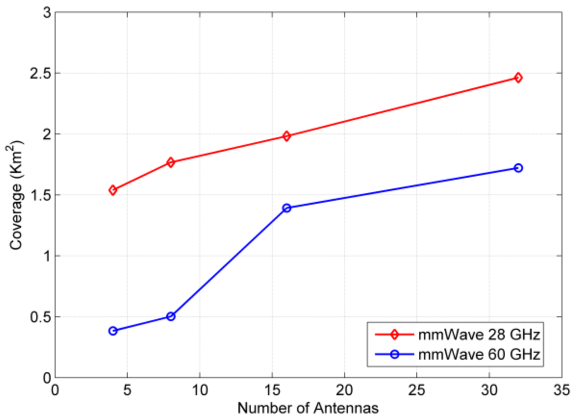


Fig. 6. Coverage for 20 users with the different numbers of antennas: (a) mmWave 28 GHz and (b) mmWave 60 GHz.

4.2. SINR

SINR is obtained from the Matlab simulation results by calculating the received power at the receiver (in blue). First, the received power is calculated at the desired base station where the other base stations are interfering. Interference is the unintended reception of the same frequency caused by multipath propagation until it reaches the receiver. In this calculation, the SINR calculation model is shown in Fig. 7, where transmission from BS (red) to BS (blue) with a green color path (dashed red circle) is the desired signal, while the other red base stations do not transmit but become interfere with the beam direction used with angles of 30, 150, and 270 degrees. The desired receiving power is then divided by the noise receiver power added to the total interference power.

Figure 8 shows the SINR at frequencies of 28 and 60 GHz for the different numbers of mmWave MIMO antenna elements, namely 4, 8, 16, and 32. In general, the signal quality of the mmWave MIMO network will be higher as the number of elements used increases. Then, the SINR generated by the mmWave MIMO 28 GHz network is higher than the 60 GHz network. For example, for a 4-element antenna, the SINR at 28 GHz is 24.57 dB, while the SINR at 60 GHz is 14.28 dB. Then the SINR gap between the two frequencies is significantly different, which is 10.29 dB. However, the SINR difference will be smaller when there are many mmWave MIMO antennas, for example, 32 dB, where the SINR at 28 GHz is 28.58 dB, and the SINR at 60 GHz is 25.95 dB. Then the difference in SINR on the two network frequencies is getting smaller, namely: 2.63 dB. A high SINR will result in better-received signal quality.

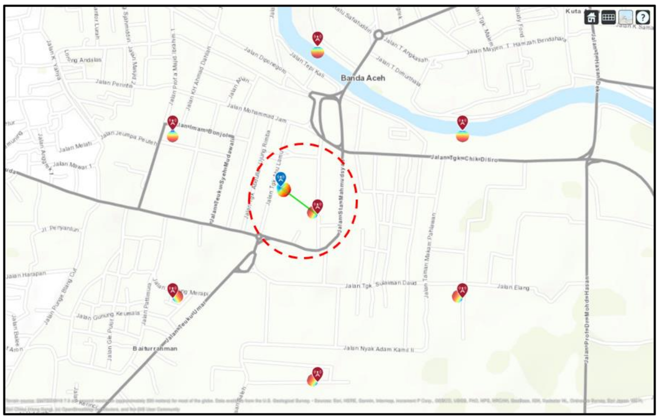


Fig. 7. SINR patterns mmWave MIMO with 8-antenna.

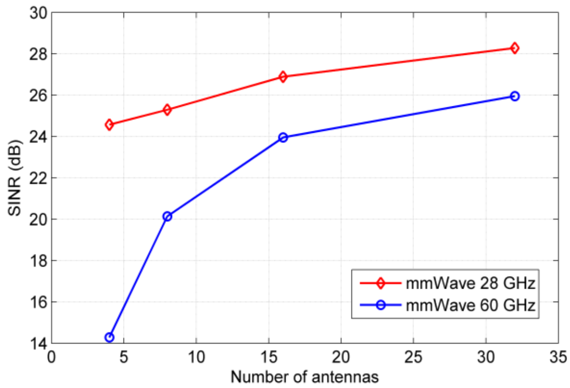


Fig. 8. SINR performance for mmWave MIMO 28 dan 60 GHz.

4.3. Throughput

The throughput simulation results of the mmWave MIMO network at frequencies of 28 and 60 GHz can be seen in Fig. 9. The resulting throughput indicates that the greater the number of antenna elements, the greater the throughput. Consequently, the mmWave MIMO network at 60 GHz has a higher throughput than the mmWave MIMO network at 28 GHz. In addition, the difference in throughput between the two frequencies will grow as the number of antenna elements increases. For instance, the throughput of a 4-element antenna at 28 GHz and 60 GHz is 24.24 Mbps and 45.90 Mbps, respectively, for a difference of 21.66 Mbps in throughput. Using 32 antenna elements, the throughput for each frequency of 28 and 60

GHz is 98.25 Mbps and 194.88 Mbps, respectively. This demonstrates that the throughput of the 60 GHz mmWave MIMO network is nearly double that of the 28 GHz mmWave MIMO network. Consequently, if throughput is vital to the mmWave MIMO network, the 60 GHz frequency is the optimal choice.

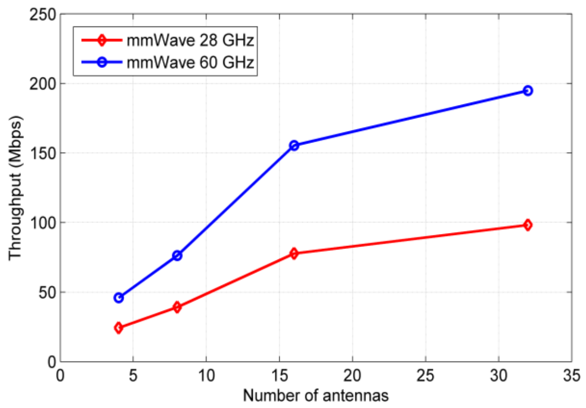


Fig. 9. Throughput of mmWave MIMO 28 dan 60 GHz.

4.4. Energy Efficiency

As previously mentioned, energy efficiency is important in designing high-frequency mmWave MIMO. However, energy efficiency is highly dependent on the network's energy consumption level and is also influenced by the number of MIMO antennas used. For this reason, the power consumed by the network is calculated by Eq. (9) for the number of antennas: 4, 8, 16, and 32. The simulation results of power consumption on each mmWave MIMO network are shown in Fig. 10.

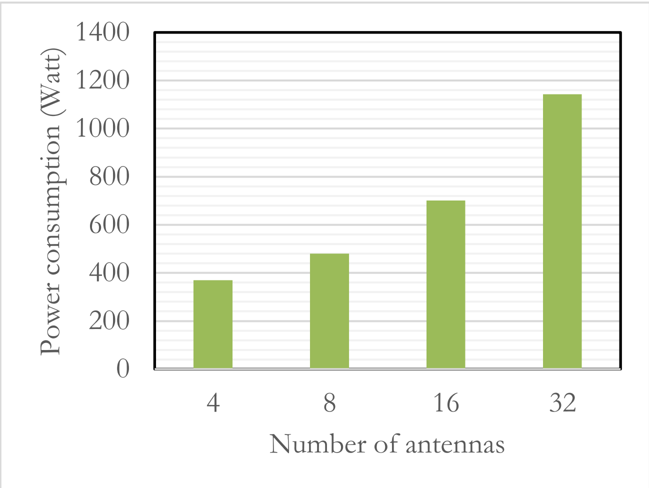


Fig. 10. Power consumption of mmWave MIMO with various antennas.

Figure 10 shows the power consumption of 4, 8, 16, and 32 antennas on the mmWave MIMO network, 370, 480, 701, and 1143 W, respectively. The results of this power consumption will be used to determine energy efficiency. In addition, energy efficiency is affected by the coverage area of the base station, the number of users, the bit rate, and the throughput of each mmWave MIMO 28 and 60 GHz network. The results of the energy efficiency simulation can be seen in Fig. 11.

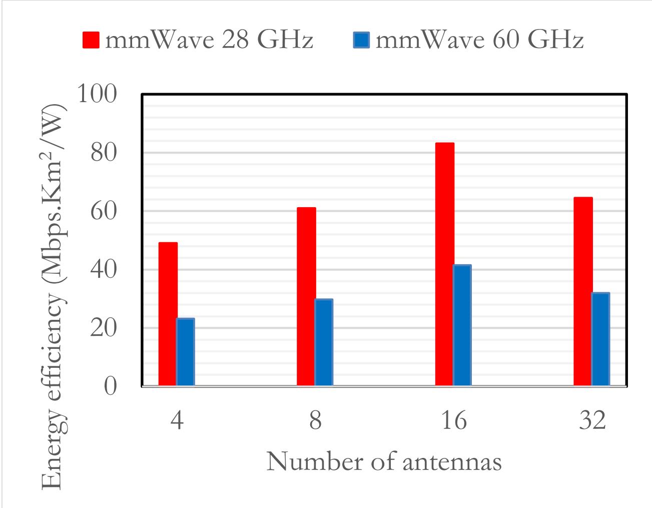


Fig. 11. Energy efficiency of mmWave MIMO 28 and 60 GHz.

Figure 11 shows the energy efficiency of the 28 and 60 GHz mmWave MIMO network based on the coverage area that has been simulated in Fig. 5. The number of antenna elements in a mmWave MIMO network has a significant impact on its effectiveness. However, multiple antenna elements do not always result in high energy efficiency. For example, the energy efficiency of both mmWave MIMO networks increases when the number of antenna elements is increased to 16, but decreases when the number of antenna elements is increased to 32. Using a 16-element antenna, mmWave MIMO networks on either the 28 or 60 GHz frequency band are thus energy efficient. The mmWave MIMO 28 GHz network is therefore more energy effective than the mmWave MIMO 60 GHz network. With 16 antenna elements, the energy efficiency of the 28 GHz and 60 GHz mmWave MIMO networks is 83,132 and 41,568 Mbps.Km^2/Watt, respectively. Then, the average energy efficiency of the mmWave MIMO 28 GHz network for all antenna elements is approximately twice that of the mmWave MIMO 60 GHz network.

Table 4 summarizes the results of the performance evaluation of the mmWave MIMO network design for the 28 and 60 GHz frequencies. Except for throughput parameters, the summary results indicate that the 28 GHz mmWave MIMO network has several advantages over the 60 GHz mmWave MIMO network. Therefore, the mmWave MIMO 28 GHz network could be implemented in urban areas, particularly in Banda Aceh City.

Table 4. Summary performance factors of mmWave MIMO 28 and 60 GHz networks.

Performance indicator	28 GHz	60 GHz
Coverage	wider	narrow
SINR	high	low
Throughput	low	high
Efficiency energy	high	low

5. Conclusions

This paper has designed and evaluated mmWave MIMO networks for 28 and 60 GHz frequencies in an urban area. The designed mmWave MIMO network takes into account multiple base stations (BS) in an urban location (a case study of the city of Banda Aceh), with each BS serving 20 user equipment (UEs). For the operational viability of the designed network, crucial parameters such as network parameters, coverage, and BS power consumption have been considered. The performance parameters of the designed mmWave MIMO network were then evaluated based on coverage, SINR, throughput, and energy efficiency. The network performance was evaluated using Matlab programming for the mmWave MIMO with different antenna elements: 4, 8, 16, and 32. The simulation results indicate that the number of antennas impacts the performance of mmWave MIMO networks operating at 28 GHz and 60 GHz. The performance evaluation revealed that the mmWave MIMO 28 GHz network offers superior coverage, SINR, and energy efficiency compared to the mmWave MIMO 60 GHz network. Additionally, the mmWave MIMO 28 GHz network has the maximum energy efficiency with its sixteen antennas. However, the transmission of the mmWave MIMO 28 GHz network is less than that of the mmWave MIMO 60 GHz network. However, the mmWave MIMO 28 GHz network is more prospective for implementation in urban areas than the mmWave MIMO 60 GHz network, particularly in Banda Aceh city.

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References

[1] G. H. Sim, A. Loch, A. Asadi, V. Mancuso, and J. Widmer, "5G millimeter-wave and D2D symbiosis: 60 GHz for proximity-based services," *IEEE Wireless Communications*, vol. 24, no. 4, pp. 140-145, Aug. 2017.

[2] N. Shoaib, S. Shoaib, R. Y. Khattak, I. Shoaib, X. Chen, and A. Perwaiz, "MIMO antennas for smart 5G devices," *IEEE Access*, vol. 6, pp. 77014–77021, 2018.

[3] M. J. Riaz, A. Sultan, M. Zahid, A. Javed, Y. Amin, and J. Loo, "MIMO antennas for future 5G communications," in *2020 IEEE 23rd International Multitopic Conference (INMIC)*, Nov. 2020, pp. 1–4.

[4] X. Lu *et al.*, "Integrated use of licensed- and unlicensed-band mmWave radio technology in 5G and beyond," *IEEE Access*, vol. 7, pp. 24376–24391, 2019.

[5] W. Hong *et al.*, "The role of millimeter-wave technologies in 5G/6G wireless communications," *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 101–122, Jan. 2021.

[6] M. I. Khan *et al.*, "A compact mmWave MIMO antenna for future wireless networks," *Electronics*, vol. 11, no. 15, Jan. 2022, Art. no. 15.

[7] N. Cardona, L. M. Correia, and D. Calabuig, "Key enabling technologies for 5G: Millimeter-wave and massive MIMO," *Int J Wireless Inf Networks*, vol. 24, no. 3, pp. 201–203, Sep. 2017.

[8] Y. Sun and C. Qi, "Weighted sum-rate maximization for analog beamforming and combining in millimeter wave massive MIMO communications," *IEEE Communications Letters*, vol. 21, no. 8, pp. 1883-1886, Aug. 2017.

[9] S. A. Busari, K. M. S. Huq, S. Mumtaz, L. Dai, and J. Rodriguez, "Millimeter-wave massive MIMO communication for future wireless systems: A survey," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 2, pp. 836–869, 2018.

[10] J.-H. Lee, J.-S. Choi, J.-Y. Lee, and S.-C. Kim, "28 GHz millimeter-wave channel models in urban microcell environment using three-dimensional ray tracing," *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 3, pp. 426–429, Mar. 2018.

[11] F. Erden, O. Ozdemir and I. Guvenc, "28 GHz mmWave Channel Measurements and Modeling in a Library Environment," *2020 IEEE Radio and Wireless Symposium (RWS)*, San Antonio, TX, USA, 2020, pp. 52-55.

[12] P. Zhang, J. Li, H. Wang, and W. Hong, "Measurement-based propagation characteristics at 28 GHz and 39 GHz in suburban environment," in *2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, Jul. 2019, pp. 2121–2122.

[13] S. Ullah, W.-H. Yeo, H. Kim, and H. Yoo, "Development of 60-GHz millimeter wave, electromagnetic bandgap ground planes for multiple-input multiple-output antenna applications," *Sci Rep*, vol. 10, no. 1, Art. no. 1, May 2020.

[14] S. Lavdas, P. K. Gkonis, Z. Zinonos, P. Trakadas and L. Sarakis, "An adaptive hybrid beamforming approach for 5G-MIMO mmWave wireless cellular networks," *IEEE Access*, vol. 9, pp. 127767-127778, 2021.

[15] R. Ilyas, A. Malik, A. A. Alammari, and M. Sharique, "5G and mmWave MIMO channel models: Simulations and analysis," in *2021 Sixth International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)*, Mar. 2021, pp. 435–440.
[16] J.-H. Kwon *et al.*, "Spectral and energy efficient power allocation for MIMO broadcast channels with individual delay and QoS constraints," *Journal of Communications and Networks*, vol. 22, no. 5, pp. 390–398, Oct. 2020.
[17] F. Richter, A. J. Fehske, and G. P. Fettweis, "Energy efficiency aspects of base station deployment strategies for cellular networks," in *2009 IEEE 70th Vehicular Technology Conference Fall*, Sep. 2009, pp. 1–5.
[18] S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter-wave cellular wireless networks: Potentials and challenges," *Proceedings of the IEEE*, vol. 102, no. 3, pp. 366–385, Mar. 2014.
[19] T. E. Bogale and L. B. Le, "Massive MIMO and mmWave for 5G wireless HetNet: Potential benefits and challenges," *IEEE Vehicular Technology Magazine*, vol. 11, no. 1, pp. 64–75, Mar. 2016.
[20] R. L. Freeman. *Radio System Design for Telecommunications*, 3rd ed. Wiley, 2007.
[21] G. R. Maccartney, T. S. Rappaport, M. K. Samimi and S. Sun, "Millimeter-wave omnidirectional path loss data for small cell 5G channel modeling," in *IEEE Access*, vol. 3, pp. 1573-1580, 2015.
[22] Y. Banday, G. M. Rather, and G. R. Begh, "SINR analysis and interference management of macrocell cellular networks in dense urban environments," *Wireless Pers Commun.*, vol. 111, pp. 1645–1665, 2020.
[23] Z. Zhang, J. Ryu, S. Subramanian, and A. Sampath, "Coverage and channel characteristics of millimeter wave band using ray tracing," in *2015 IEEE International Conference on Communications (ICC)*, Jun. 2015, pp. 1380–1385.
[24] S. K. Agrawal and K. Sharma, "5G millimeter wave (mmWave) communications," *2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom)*, New Delhi, India, 2016, pp. 3630-3634.

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