

On the Spectral and Energy Efficiency Analysis of Statistical Clustered-Based MIMO Channel

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ABSTRACT

The Multiple-Input Multiple-Output technology played a key role in the accomplishment of user-high data rates. In the evolution of cellular technology to future wireless communication and beyond, the utilization of millimeter waves has been projected to deliver a better performance in terms of capacity and latency. However, the development of this technology is limited by the system's power consumption. The purpose of this study is to examine the impact of clustered channels utilization in terms of spectral and energy efficiency. In this paper, we study the performance of clustered-based channel using multiple antennas by evaluating the spectral efficiency, throughput, and energy efficiency in macrocell (UMa), microcell (UMi), indoor office, and indoor shopping mall scenarios. The simulation result shows that the performance of the system in the UMi type of environment scenario outperforms other scenarios in which 90% of bandwidth utilization reaches 24 bits/s/Hz. Furthermore, the result shows, in UMi deployment, the increase of spectral efficiency is in line with the escalation of the number of antennas and transmit power, which achieves the best spectral utilization at 16x40 antennas and 10 dB, respectively. However, these scenarios consumed most power among others, which is the trade-off of the system.

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1. INTRODUCTION

The amount of communication traffic carried by the wireless network has been significantly increasing, which includes and is not limited to video streaming services, online gaming, instant messaging, and Voice over Internet Protocol (VoIP). These types of services are highly dependent on the reliability of the network connectivity which is supported by Multiple-Input Multiple-Output (MIMO) technology. The MIMO technology enables the communication system to transmit several signals from multiple antennas as transmitters and receivers, in a single radio channel [1]. To add more, as cellular technology has moved to 5G, the use of millimeter waves will open the opportunity to achieve multi-Gigabit-per-second [2,3]. The spectrum of millimeter waves technically ranges from 30 to 300 GHz. With smaller wavelengths, the traffic transmission through millimeter waves may use a new spatial processing technique that can provide greater capacity. However, communication through millimeter waves requires a new understanding of channel propagation as the behavior of the channel is different from the currently used frequency spectrum, ranging from 700 MHz to 2.6 GHz [4].

Similar to spectrum frequency as a scarce resource, the availability of energy resources is also one of the main concerns of cellular technology development. The limitation of energy resources is unavoidable causing the restriction to bandwidth expansion [5,6]. Therefore, it is essential to investigate

the performance of wireless communication in the relation to the system energy usage. Better schemes of power consumption is continuously worked on to achieve more efficient energy usage.

Several works have been conducted related to utilizing millimeter waves in 5G communication. The feasibility of utilizing millimeter waves in 5G communication has been put forward by [6] and the technical aspect of millimeter utilization has been discussed in [7, 8, 9, 10]. Jijo et al. has done a comprehensive study on the challenges of 5G millimeter wave [11]. The propagation parameters and channel models for understanding millimeter wave propagation are investigated by [12, 13, 14]. The statistical procedure for generating a clustered MIMO channel model operating at a millimeter wave is proposed in [15]. The study to find the comparison between energy efficiency and spectral efficiency in a heterogeneous network is conducted by [16, 17, 18, 19, 20]. However, the study of energy and spectra on clustered-based channels is still lacking. At this point, it is important to also investigate the relationship between energy and spectral efficiency in a clustered MIMO network operating in millimeter waves, which is the main purpose of this work.

2. RESEARCH METHOD

The work of this study focuses on the performance evaluation of the channels propagation of clustered MIMO channel operating at millimeter waves, concerning spectral efficiency and energy efficiency. The research is conducted by simulating the MIMO channel matrix for linear time-invariant clustered channel model, along with their path loss components. Next, the achievable user rate can be obtained and the spectral efficiency of the system can be measured. Finally, after measuring the throughput and power consumption, the system's energy efficiency is accomplished.

2.1. Clustered MIMO Channel Model

MIMO array is commonly spacious in size, especially massive MIMO which consists of more than eight antennas to offer benefits to multiple simultaneous users. Consequently, as mentioned in [21], a certain amount of cluster paths of the MIMO channel are only visible to some parts of the array, referred to as non-common clusters. However, there are also cluster paths that contain all the signal paths from the whole multiple antennas, namely common clusters. As shown in Figure 1, a single cluster consists of several signal rays and there can be several clusters for an instantaneous time frame. Multipath clusters are defined as propagation paths that have similar angles and delays [21].

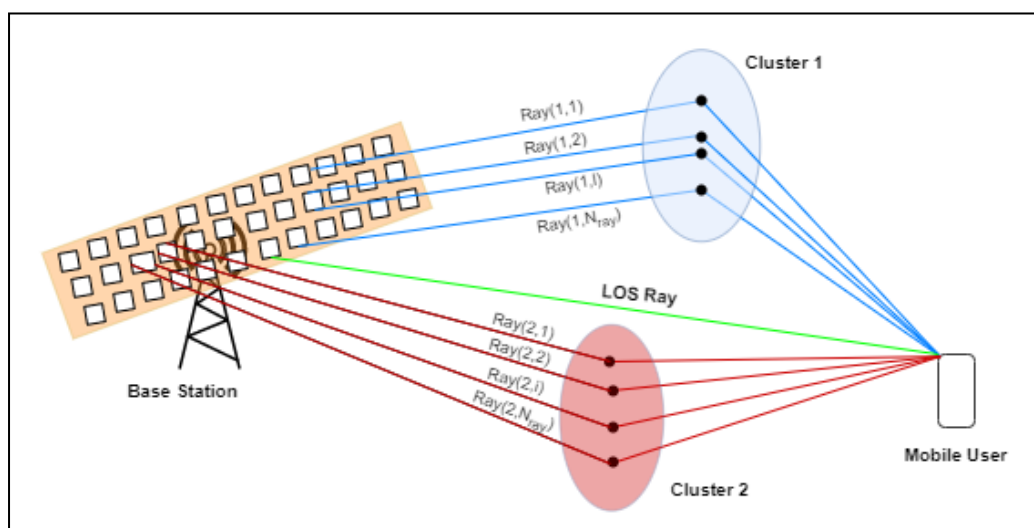


Figure 1. Illustration of clustered-based MIMO channel

In this work, the simulation environment is built based on the work by [15] which consists of a MIMO network with several multiple antennas, N_{TX} and N_{RX} , as the number of transmitter antennas, and receiver antennas, respectively. During the transmission of the signal, there will be several channel clusters, N_{cl} , and each cluster contains several N_{ray} signal paths. The propagation environment is the combination of Line of Sight (LOS) components and Non-LOS (NLOS) components associated with

distinct scatters. On the user's side, when there is a communication link from the BS to the user, i.e. downlink communication, a signal which arrived at the user fashions an azimuth angle and elevation angle, denoted by $\Phi_{i,l}^r$ and $\theta_{i,l}^r$, respectively, for l^{th} signal ray and i^{th} cluster. When the user's mobile phone transmits signals to the BS, the signals also form an azimuth angle and elevation angle, denoted by $\Phi_{i,l}^t$ and $\theta_{i,l}^t$. The linear-time-invariant channel matrix, $\mathbf{H}(\tau)$, can be written as:

$$\mathbf{H}(\tau) = \gamma \sum_{i=1}^{N_{cl}} \sum_{l=1}^{N_{ray}} \alpha_{i,l} \sqrt{PL(f, r_{(i,l)})} \mathbf{a}_r(\Phi_{i,l}^r, \theta_{i,l}^r) \times \mathbf{a}_t^H(\Phi_{i,l}^t, \theta_{i,l}^t) h(\tau - \tau_{i,l}) + \mathbf{H}_{LOS}(\tau) \quad (1)$$

Where γ is a normalization factor to linearly scale signal power with the product of $N_{RX}N_{TX}$, whose value is based on [22]. $\alpha_{i,l}$ is the complex path gain, $\mathbf{a}_r(\Phi_{i,l}^r, \theta_{i,l}^r)$ and $\mathbf{a}_t^H(\Phi_{i,l}^t, \theta_{i,l}^t)$ are the normalized array response vectors evaluated at the corresponding angle of arrival and departure signal, respectively. $h(\tau - \tau_{i,l})$ is the $\tau_{i,l}$ delayed version of channel response which is attained by a convolution between the channel baseband of transmit waveform, $h_{(TX)}(t)$, and the channel baseband of the receive filter signal waveform $h_{(RX)}(t)$. $PL(f, r_{(i,l)})$ is the path loss (PL) associated with the (i, l) -th propagation path, which will be specified in the next section. $\mathbf{H}_{LOS}(\tau)$ is the channel matrix for the LOS condition, which is written as [15]:

$$\mathbf{H}_{LOS}(\tau) = I_{LOS}(d) \sqrt{N_{RX}N_{TX}} e^{j\eta} \sqrt{PL_{LOS}} \mathbf{a}_r(\Phi_{LOS}^r, \theta_{LOS}^r) \times \mathbf{a}_t^H(\Phi_{LOS}^t, \theta_{LOS}^t) h(\tau - \tau_{LOS}) \quad (2)$$

With η is uniformly distributed phase, PL_{LOS} is the attenuation of a signal transmitted from the transmitter and receiver without the existence of obstructions, which is called free space loss (FSPL). $I_{LOS}(d)$ is a parameter that indicates if there is a LOS link between BS and the user. The setting p is the probability of LOS link occurrence, which will give $I_{LOS}(d) = 1$. The existence of the LOS link will depend on the deployment scenarios. In this paper, the scenarios are simulated for four different types, i.e. Urban Macrocellular (UMa), Urban Microcellular (UMi), Indoor Hotspot (InH) Office, and InH Shopping Mall. The value of p for each scenario follows [23] which is written in Table 1.

Table 1. Calculation of p for different scenarios

UMa	$p = \left(\min\left(\frac{18}{d}, 1\right) \left(1 - e^{-\frac{d}{63}}\right) + e^{-\frac{d}{63}} \right), \text{ for receiver height} = 1 \text{ meter}$
UMi	$p = \min\left(\frac{20}{d}, 1\right) \left(1 - e^{-\frac{d}{39}}\right) + e^{-\frac{d}{39}}$
InH	$p = \begin{cases} 1, & d \leq 1.2 \\ e^{-\left(\frac{d-1.2}{4.7}\right)}, & 1.2 \leq d \leq 6.5 \\ 0.32e^{-\left(\frac{d-6.5}{32.6}\right)}, & d \geq 6.5 \end{cases}$

where d is the distance between the transmitter and the receiver.

2.2. Path Loss Model

Path loss is defined as the signal power lost due to the dissipation of the transmitter power and the effects of the propagation channel [24, 25]. The simplest path loss model for signal propagation is FSPL which the signal propagation path between transmitter and receiver forms a straight line, without any obstacles. The other common path loss models are the Ray-tracing model and the empirical model. The ray-tracing model depends on the geometry and the dielectric properties of the region where the signal propagates. The empirical model is built upon the realistic measurement of the indoor and outdoor propagation channels.

As the technology of wireless communication is continuously evolving, the path loss model for 5G communication is also developed. The channel models for the 5G network for frequency up to 100 GHz has been derived [23]. The path loss model for the system that is used in this work is a close-in free (CIF) space reference distance model with frequency-dependent path loss exponent [23, 26], given by:

$$PL(f, r_{(i,l)})[dB] = FSPL(f, 1 \text{ m}) + 10n \left(1 + b \left(\frac{f-f_0}{f_0} \right) \right) \log_{10} \left(\frac{r_{(i,l)}}{1 \text{ m}} \right) + X_\sigma \quad (3)$$

Where $PL(f, r_{(i,l)})$ is the path loss for cluster i -th and array l -th, $FSPL(f, 1 m)$ is the free space path loss (FSPL) for d is 1 meter, n is the path loss exponent, b denotes the system parameter that captures the slope, f_0 is the reference frequency, $r_{(i,l)}$ is the path length for a signal path in cluster i -th and array l -th, and X_σ is the shadow fading in dB. $r_{(i,l)}$ is calculated based on the geometrical properties, depending on the height of BS and user's terminal.

The values for the parameters in (3) for each scenario are based on the previous related works [23], [26], as presented in Table 2.

Table 2. Model Parameters for Different Scenarios

Scenario	Value Parameter n	Value Parameter b	Value Parameter f_0	Value Parameter X_σ
UMa	3.0	0	49 GHz	6.8 dB
UMi	3.19	0	49 GHz	8.2 dB
InH Office	3.19	0.06	24.2 GHz	8.29 dB
InH Shopping Mall	2.59	0.01	39.5 GHz	7.40 dB

2.3. Spectral Efficiency

Based on [27], spectral efficiency is defined as the average number of bits that can be transmitted per complex-valued sample, measured in bit/s/Hz. For the complex-baseband signal representation, B complex-valued samples per second are legitimate [28]. The maximum spectral efficiency is determined by the channel capacity which relates to the information rate of the system.

The baseband equivalent of the received signal at time sampling n is written as [15]:

$$\mathbf{r}(n) = \sum_{l=0}^{P-1} \mathbf{D}^H \mathbf{H}(l) \mathbf{Q} \mathbf{s}(n-l) + \mathbf{D}^H \mathbf{w}(n) \quad (4)$$

Where P is the length of the channel, $\mathbf{D}$ is the combining matrix and $\mathbf{Q}$ is the precoding matrix. The dimension of $\mathbf{D}$ and $\mathbf{Q}$ depend on the dimension of antenna elements in the BS and the user's terminal, respectively. $\mathbf{s}(n)$ is the vector of the data symbol, transmitted from the BS at the time n , with the dimension of M the number of information symbols. $\mathbf{w}(n)$ is the additional noise vector. To obtain the estimation of $\mathbf{s}(n)$, i.e. $\hat{\mathbf{s}}(n)$, the Linear Minimum Mean-Squared Error (LMMSE) using a matrix estimator $\mathbf{E}$, which aims to minimize mean-squared error (MSE) $\mathbb{E} \|\mathbf{s}(n) - \hat{\mathbf{s}}(n)\|^2$. $\hat{\mathbf{s}}(n)$ can be written as $\hat{\mathbf{s}}(n) = \mathbf{E}^H \mathbf{A} \mathbf{s}(n) + \mathbf{E}^H \mathbf{A}_I \mathbf{s}_I(n) + \mathbf{E}^H \mathbf{B} \mathbf{w}$. The first term contains $\mathbf{A}$, as the desired symbols. The second term consists of $\mathbf{A}_I$ and $\mathbf{s}_I(n)$ are a signature matrix and the symbol, respectively, appeared due to interference. The third term is the noise component. The information rate at the user's terminal is expressed as [15], [29]:

$$\mathcal{R} = \log_2 \det \left[\mathbf{I}_M + \left| \mathbf{E}^H \left(\frac{P_T}{M} \mathbf{A}_I \mathbf{A}_I^H + \sigma_N^2 \mathbf{B} \mathbb{E}[\mathbf{w}(n) \mathbf{w}^H(n) \mathbf{B}^H] \right) \mathbf{E} \right|^{-1} \left(\frac{P_T}{M} \mathbf{E}^H \mathbf{A} \mathbf{A}^H \mathbf{E} \right) \right] \quad (5)$$

Where P_T is the transmit power and $\mathbf{B}$ is the available bandwidth. By normalizing the user's information rate to the bandwidth $\mathbf{B}$, the achievable spectral efficiency can be obtained.

2.4. Energy Efficiency

"The energy efficiency of a cellular network is the number of bits which can reliably transmitted per unit energy" [27]. The energy efficiency can be measured by:

$$\text{Energy Efficiency (bit/Joule)} = \frac{\text{Bandwidth} \times \text{Spectral Efficiency (bit/s)}}{\text{Power Consumption (Watt)}} \quad (6)$$

Equation (6) shows that the energy efficiency indicates the efficiency of delivering bits from the transmitter and the receiver. The power consumption (PC) of the system is calculated by [27]:

$$PC = ETP + CP \quad (7)$$

Where ETP is effective transmit power, i.e. transmit power of the BS, and CP is the circuit power. In this work, the CP model of a BS follows [27] which is composed of power consumption of fixed power, transceiver chains, channel estimation, signal processing, coding/decoding, load-dependent

backhaul, and signal processing. The values of those parameters are based on [27] for the MMSE scheme. The total CP in single cell MMSE is 26.51 Watts for 100 multiple antennas.

3. RESULTS AND DISCUSSION

This section provides the simulation results of the system model described in prior. In this work, we consider 73 GHz carrier frequency and there are 6 data symbols in each transmission. In the Uma scenario, the height of BS h_{TX} , is 30 meters, and the height of the user's terminal, h_{RX} , is 1 meter, and d is 60 meters. For UMi, InH Office, and InH Shopping Mall scenario, h_{TX} is 7 meters, h_{RX} is 1 meter and d is 5 meters.

Figure 2 presents the Cumulative Distribution Function (CDF) of the spectral efficiency for four different scenarios simulated in this work when the user's terminal has 20 multiple antennas and there are 40 multiple antennas in the BS. It can be observed that the spectral efficiency of UMi scenario outperforms other scenarios. In UMi deployment, 90% of bandwidth utilization reaches 24 bits/s/Hz. However, those value is not much different for the InH Shopping Mall scenario. In the scenario of InH Office, there is around 18 bits/s/Hz for the same portion of bandwidth usage. The last performance occurs in the UMa scenario in which 90% of users receive around 7 bits/s/Hz, and achieve only 10 bits/s/Hz at maximum. The distinguished performance of the UMi deployment can be the result of a shorter range of BS's transmit power hence the propagation is less. While for indoor deployment, the performance is influenced by the walls blocking the signals and the materials of the building.

The performance of the clustered-based channel is also evaluated by varying the number of antenna elements having a UMi scenario. In Figure 3, it can be observed that as the amount of antenna elements increases, the user is able to achieve a higher data rate. For 16x40 MIMO, the user's achievable rate is the highest as many as 17 Mbps, compared to other MIMO schemes. The increase of user data rate in this work is similar to the spectral efficiency performance in [15], in which the rise of spectral efficiency is in line with the increment of the number of antennas. However, for a 16x40 MIMO scenario, the energy efficiency only reaches around 1 Mbit per Joule, which is the lowest performance. By using 16x16 MIMO, the system is able to perceive the most efficient energy usage with 1.5 Mbit per Joule. This happens in line with the fact that the system power consumption escalates in magnitude as the rise of number of antenna elements. Although the user's rate can be improved by adding multiple antennas, the efficiency of the energy in power usage will be the trade-off.

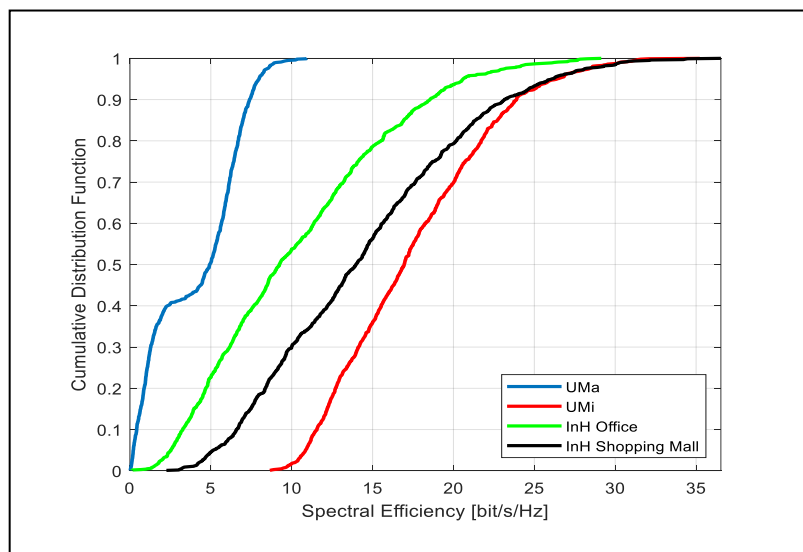


Figure 2. CDF of spectral efficiency for different deployment scenarios

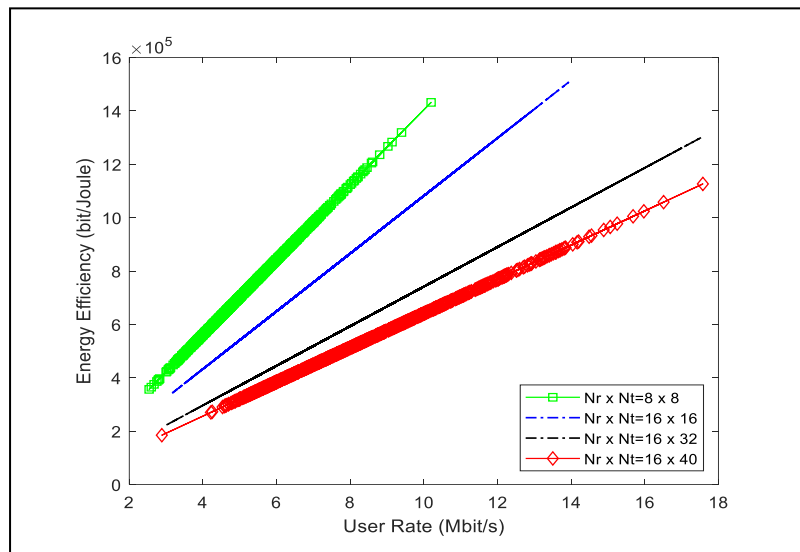


Figure 3. Energy efficiency as a function of achievable user rate for different number of antenna elements

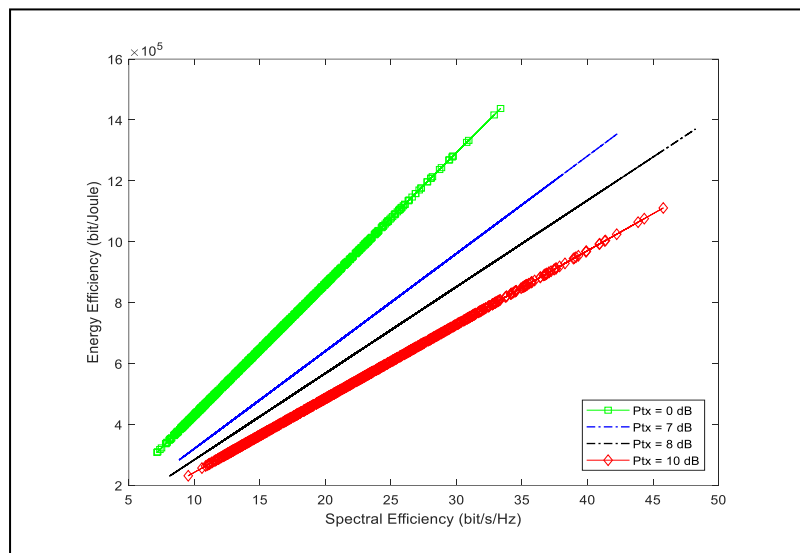


Figure 4. Energy efficiency versus spectral efficiency for different cases of BS transmit power

Figure 4. presents the spectral and energy efficiency considering different schemes of transmit power with fixed 40x40 antenna elements in MIMO. With higher power transmitted by the BS, the spectral efficiency also scales up as the user experiences a better information rate. Among various values of transmit power simulated in this work, using 8 dB transmit power results in a spectrum efficiency of 48 bit/s/Hz which outperforms other transmit power schemes, while having around 1.3 Mbit per Joule which is not much different when using 0 dB and 7 dB transmit power. This result is similar to the one conducted by [30] which for higher transmit power there is a trade-off between spectral and energy efficiency for cell-free massive MIMO. However, the simulation conducted in this study does not include the velocity of moving users which is the limitation of this work.

4. CONCLUSION

This research is conducted to investigate the performance of the cluster-based channel in the MIMO system operating in millimeter waves in terms of spectral and energy efficiency. Based on the simulation on UMa, UMi, InH Office, and InH Shopping Mall scenarios, the deployment of the clustered channel on UMi has the best performance where 90% of users can achieve 24 bits/s/Hz spectral efficiencies,

which can be caused by the shorter range of BS's transmit power. Moreover, by controlling several system parameters in the simulation including schemes of environment type, the number of antenna elements in MIMO, and the power transmitted by the BS, it can be concluded that there is a trade-off between spectral efficiency and energy efficiency. Having a good efficiency in spectrum utilization, there will be the price in the low efficiency of energy usage. However, by increasing the number of antennas and BS transmit power, the performance of energy efficiency does not always surpass those with lower power, as shown in the simulation result above that by using 16x40 MIMO antennas and 10 dB transmit power, the performance of energy efficiency is the least among others. Hence, this research has contribution in the selection of values of related parameters considered when designing the cluster-based channel MIMO system.

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