Spatial Modulation and Spatial Multiplexing Capacity Analysis over 3D mmWave Communications

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University of Benghazi, Electrical and ...

P.O. Box: 7051 Bengha...

[2] German Jordanian University, Electrical and Communications Engineering Department,

School of Electrical Engineering and Information Technology,

P.O. Box 35247, Amman 11180 Jordan, E-mails: raed.mesleh@gju.edu.jo

[3] Almadar Research and Development Office, Almadar Aljadid Company, E-mails: a.abouda@almadar.ly

[4] The Department of Computer Science, University of Vaasa, Finland. E-mails: moel@uwasa.fi

***Abstract*—In this paper, capacity analysis for two multiple–input multiple–output (MIMO) systems, spatial multiplexing (SMX) and spatial modulation (SM), over 3D statistical outdoor mmWave channel model is presented and compared. The theoretical capacity for each systems are derived and studied. The SM capacity is shown to be channel independent and requires proper design of the used constellation symbols for each channel statistics. Although, it is revealed that the theoretical capacity of SM is higher than that of SMX. Monte Carlo simulation results with ordinary constellation symbols, such as QAM, ascertained that SMX offers better mutual information performance than SM for the same MIMO setup.Hence, proper design of the signal constellations for SM is needed. In addition, the Energy Efficiency (EE) of both MIMO systems, SM and SMX is discussed in this paper. Obtained results show that SM can offer up to 36% and 74% enhancement in the EE compared to SMX.**

***Index Terms*—millimeter-wave (mmWave) communication, spatial modulation (SM), spatial multiplexing (SMX)**

I. Introduction

According to CISCO visual networking index (VNI) forecast (2016), mobile data traffic is expected to surpass 30.6 Exabytes per month by 2020. Also, it is forecast that there will be more than 11 billion connected devices, which will cause a huge increase in global data traffic. This increase is mainly because of the massive spread of cloud-based application ,the use of high resolution video steaming and Internet of things (IoT). This demand for broadband wireless communications is faced by the overcrowded frequency spectrum and the limited capacity of the current wireless communication systems [1, 2]. The next generation wireless system, 5G, will exploit novel technologies including millimetre–wave (mmWave) communication [3] and multiple–input multiple–output (MIMO) [4] to achieve the needed capacity, spectral efficiency requirement, and to accommodate the ever increasing demand for high–speed communication.

mmWave technology can potentially provide several gigahertz bandwidths to solve the spectrum scarcity in the current frequency bands up to 6 GHz. It offers a plentiful frequency spectrum, ranging from 24–300 GHz, that can be exploited to achieve multi–gigabits per second data rates. Moreover, mmWave will address many challenges in the current wireless communications for example : 1) very high data rates, 2) IoT, 3) mobility and availability , 4) Real–time and reliable communications in a user dense area, and 5) Low latency [5].

mm-Wave channel modeling and characterization have been attracting great attention in the literature as a promising technology for future generation of wireless systems. Currently, models such as 3D 3GPP Model, Cost 2100, METIS Model, and 3D mmWave channel model proposed by the New York University (NYU) Wireless Lab are available [6]. In this paper, the NYU channel model is considered in all studies.

The use of MIMO systems to increase the capacity of wireless communications systems has been an active area of research for over 30 years and are currently being used in the 4G systems. Such systems facilitate high–throughput transmission in various recent standards including LTE, WIMAX, and others [4]. Examples of MIMO systems are: Spatial Multiplexing (SMX) and Spatial Modulation (SM). In SMX the source data stream is divided into a number of blocks equal to the number of transmit antennas, then transmitted simultaneously from all antennas using the same carrier frequency. As a result, providing a liner increase in spectral efficiency which proportional to the available number of transmit antennas [7]. While in SM only one of transmit antenna is active at each time instance. The incoming data bits modulate a complex symbol (*constellation symbol*) from arbitrary constellation diagram. The modulated symbol is transmitted from the single active antenna, which is considered as (*spatial symbol*). Hence, the spectral efficiency increases by base two logarithm of the number of transmit antennas [8]. In addition, only one power amplifier is required at the transmitter, which causes less power consumption, since it is known that vast majority of the power at transmitter is consumed by the power amplifier [9].

Hence, combining mmWave with MIMO systems promises a significant increase in the overall achievable data rate as well as increase in reliability, and bandwidth to support next generations such as 5G and beyond.

In this paper, the capacity of SMX and SM is derived and thoroughly discussed. It is shown that SM capacity does not depend on the channel, as the different channel paths are spatial constellation symbols that are used to convey information bits. Hence, the SM capacity is shown to be achievable with proper design of the constellation diagram, such that the probability distribution function of the transmitted SM vector follows a complex Gaussian distribution. The derived capacity for SM shows that, 1) complex Gaussian distributed constellation symbols does not always achieve capacity, and 2) SM has a higher capacity than SMX. Furthermore, the performance of SMX and SM over the statistical 3D mmWave channel model is studied and analyzed in–terms of capacity. Results show that SMX offers the same or better performance than SM using ordinary QAM constellation symbols. However, this is because the constellation symbols used are not optimum, where it is shown in the paper that the capacity of SM is actually up to 7.4 bits better than SMX. Hence, signal constellations that are properly tailored for the specific nature of the considered channel would achieve higher performance than SMX.

The performance of both systems in term of Energy Efficiency (EE) is also discussed in this paper. The EE has become a prominent MIMO communication performance metrics especially when designing new wireless communication systems like 5G. Since these systems require high data–rate communication which means high energy consumption. It has been found that when the power consumption is taken into account SM outperforms SMX in term of EE .

The rest of the paper is organized as follows: Section II introduces the system models. The 3–D mmWave channel model is presented in Section III. The mutual information and capacity of both SMX and SM are derived and discussed in Section IV. Section V summarizes the results obtained along with the analysis. Finally, the paper is concluded in SectionVI.

II. System Models

A. MIMO Modulation

1) SMX: In SMX the data bit stream is divided into blocks of $\eta = N_t \log_2(M)$ bits to be transmitted at one time instant. Then, according to [10]:

i. Each $\log_2(M)$ bits are separately modulated using M–quadrature amplitude modulation (QAM) modulation.
ii. The modulated symbols are then transmitted simultaneously from the N_t transmit antennas.

2) Spatial Modulation (SM): SM activates only one transmit antenna each time instance, and transmits the symbol $s_\imath \in \mathcal{S}$ from the active transmit antenna ℓ, where $\mathcal{S}$ contains all possible constellations symbols. Thus, the spectral efficiency of SM is $\eta = \log_2 N_t + \log_2 M$ bits [8]. Note, the spatial symbol is $\mathcal{H}_\ell = \mathbf{h}_\ell$, and the constellation symbol is $\mathcal{S}_\imath = s_\imath$, where $\mathbf{h}_\ell$ is the ℓ^{th} vector of $\mathbf{H}$, and $\mathbf{H}$ is the $N_r \times N_t$ channel matrix, with N_r denoting the number of receive antennas.

The resultant vector, $\mathbf{x}_t$, is transmitted over an $N_r \times N_t$ mmWave MIMO channel matrix with a transfer function $\mathbf{H}(f)$, and experiences an N_r-dim additive white Gaussian noise (AWGN) $(\mathbf{n})$, with zero mean and variance σ_n^2 (both real and imaginary parts having a double-sided power spectral density equal to $\sigma_n^2/2$).

The received signal is given by:

$$\mathbf{y} = \mathbf{H}\mathbf{x}_t + \mathbf{n}. \tag{1}$$

Note, the signal-to-noise-ratio (SNR) at the receiver input, assuming normalized channel $E_s = \mathrm{E}[\|\mathbf{H}\mathbf{x}\|_{\mathrm{F}}^2] = N_r$, is given by $\mathrm{SNR} = E_s/N_0 = 1/\sigma_n^2$, where $\|\cdot\|_{\mathrm{F}}$ is the Frobenius norm.

B. ML–Optimum Detector

At the receiver, the maximum–likelihood (ML) optimum detector is used, which can be written as,

$$\hat{\mathbf{x}}_t = \arg\min_{\mathbf{x}\in\mathcal{Q}} \left\{ \left\| \mathbf{y} - \tilde{\mathbf{H}}\mathbf{x} \right\|_{\mathrm{F}}^2 \right\} \tag{2}$$

where $\mathcal{Q}$ contains every possible $(N_t \times 1)$ transmit vector, and $\hat{\cdot}$ denotes the estimated transmission vector.

III. 3D mmWave Channel Model

Omnidirectional antennas operating at mmWave frequencies are considered in this study. The channel impulse response $h_{n_t,n_r}(t)$ for the n_t–th and n_r–th transmit and receive antennas, respectively, can be calculated using the double–directional channel model given in [11, 12],which is also known as a parametric channel model,

$$\underset{n_t,n_r}{h}(t) = \sum_{l=1}^{L} \underset{n_t,n_r}{h^l} a_l e^{j\varphi_l} \delta(t-\tau_l)\, \delta\left(\Theta - \underset{n_t,l}{\Theta}\right) \delta\left(\Phi - \underset{n_r,l}{\Phi}\right), \tag{3}$$

where $\underset{n_t,n_r}{h^l}$ is the l–th subpath complex channel attenuation between the n_t–th and n_r–th transmit and receive antennas respectively, a_l, φ_l and τ_l are the amplitude, phase and absolute propagation delay of the l–th subpath, $\Theta_{n_t,l}$ and $\Phi_{n_r,l}$ are the vectors of azimuth/elevation angle of departure (AOD) and angle of arrival (AOA) for the n_t–th and n_r–th transmit and receive antennas, respectively; and L is the total number of multipath components. Assuming the antenna arrays at both the transmitter and the receiver are uniformly spaced with distance d, and aligned along the z–dimension, the impulse response in (3) can be reduced to,

$$\underset{n_t,n_r}{h}(t) = \sum_{l=1}^{L} \underset{n_t,n_r}{h^l} a_l e^{j\varphi_l} \delta(t-\tau_l)\, \delta\left(\theta^z - \underset{n_t,l}{\theta^z}\right) \delta\left(\phi^z - \underset{n_t,l}{\phi^z}\right), \tag{4}$$

where $\theta^z_{n_t,l}$ and $\phi^z_{n_r,l}$ denoting the elevation AOD and AOA for the n_t–th and n_r–th transmit and receive antennas respectively.

From [13] the transfer function of the impulse response in (4) is given by,

$$\underset{n_t,n_r}{h}(f) = \sum_{l=1}^{L} \underset{n_t,n_r}{h^l} a_k e^{j\varphi_l} e^{-j\frac{2\pi}{\lambda} d \left(n_t \sin\left(\theta^z_{n_t,l}\right) + n_r \sin\left(\phi^z_{n_r,l}\right)\right)} e^{-j2\pi f \tau_l}, \tag{5}$$

where λ is the carrier wavelength.

The values of a_l, φ_l, $\theta^z_{n_t,l}$, $\phi^z_{n_r,l}$, and τ_l in this paper are generated using the 3–D statistical channel model for outdoor mmWave communications derived in [6], where the frequency is 73 GHz, antenna gains are 24.5 dBi, and the distance at each particular time instance is varied equally likely in the range of [60m – 200m] [6].

Furthermore, let $\mathbf{H}^l$ be an $N_r \times N_t$ matrix containing all $h^l_{n_t,n_r}$ complex MIMO channel attenuations, then, from [12],

$$\mathbf{H}^l = \mathbf{R}_{\text{Rx}}^{1/2}\mathbf{H}_{\text{Rician}}\mathbf{R}_{\text{Tx}}^{1/2}, \qquad (6)$$

where $\mathbf{R}_{\text{Tx}}$ and $\mathbf{R}_{\text{Rx}}$ are the transmitter and receiver correlation matrices respectively, and $\mathbf{H}_{\text{Rician}}$ is a matrix whose elements obey the small–scale Rician distribution with $K = 10$ dB [14]. From [15] the correlation matrices can be calculated by,

$$R_{u,v} = e^{-j\Theta}\left(0.9e^{-|u-v|d} + 0.1\right), \qquad (7)$$

where Θ follows a uniform distribution in the range $[-\pi, \pi]$.

IV. Capacity Analysis

A. Evaluating the Mutual Information

The mutual information of SMX system, $I(\mathbf{x}_t;\mathbf{y})$, is the number of bits that can be decoded without any errors at the receiver, and it is given by,

$$\begin{aligned} I(\mathbf{x}_t;\mathbf{y}) &= \mathrm{E}_{\mathbf{H}}\left\{I\left(\mathbf{x}_t;\mathbf{y}\,|\mathbf{H}\right)\right\} \\ &= \mathrm{E}_{\mathbf{H}}\left\{H\left(\mathbf{y}\,|\mathbf{H}\right) - H\left(\mathbf{y}\,|\mathbf{x}_t,\mathbf{H}\right)\right\}, \end{aligned} \qquad (8)$$

where $H(\cdot)$ is the entropy function.

After some manipulations,detailed in Appendix A, $I\left(\mathbf{x}_t;\mathbf{y}\,|\mathbf{H}\right)$ is,

$$I\left(\mathbf{x}_t;\mathbf{y}\,|\mathbf{H}\right) = \eta - N_r\log_2(e) - \mathrm{E}_{\mathbf{y}}\left\{\log_2\sum_{\mathbf{x}_t\in\mathcal{Q}} e^{\frac{-\|\mathbf{y}-\mathbf{H}\mathbf{x}_t\|_{\mathrm{F}}^2}{\sigma_n^2}}\right\}. \qquad (9)$$

In SM the channel paths are used as a spatial constellation symbols and modulated by the incoming data bits to convey information. Thereby, the mutual information for SM systems is given by,

$$I\left(\mathcal{H}_\ell,\mathcal{S}_\imath;\mathbf{y}\right) = H\left(\mathbf{y}\right) - H\left(\mathbf{y}|\mathcal{H}_\ell,\mathcal{S}_\imath\right), \qquad (10)$$

where $H(\cdot)$ is the entropy function.

Following the same algebraic manipulations given in Appendix A, $I\left(\mathcal{H}_\ell,\mathcal{S}_\imath;\mathbf{y}\right)$ is,

$$I\left(\mathcal{H}_\ell,\mathcal{S}_\imath;\mathbf{y}\right) = \eta - N_r\log_2(e) - \mathrm{E}_{\mathbf{y}}\left\{\log_2\sum_{\substack{\mathcal{H}_\ell\in\mathcal{H}\\ \mathcal{S}_\imath\in\mathcal{S}}} e^{\frac{-\|\mathbf{y}-\mathcal{H}_\ell\mathcal{S}_\imath\|_{\mathrm{F}}^2}{\sigma_n^2}}\right\} \qquad (11)$$

Unfortunately, for the summation in (9) and (11) no closed–form solution is available and numerical methods should be used.

It is important to note that unlike SMX in (8), in (10) for SM there is no averaging over the channel as the channel is part of the transmitted information.

B. Capacity

1) Spatial Multiplexing: By definition, the capacity is the maximum number of bits that can be transmitted without any errors, and is given by [16],

$$C = \max_{p_{\mathbf{x}_t}} I\left(\mathbf{x}_t;\mathbf{y}\,|\mathbf{H}\right), \qquad (12)$$

where the maximization is done over the choice of $p_{\mathbf{x}_t}$, with $p_{\mathbf{x}_t}$ being the probability distribution function (PDF) of the transmitted vector $\mathbf{x}$.

Substituting (8) in (12), the capacity for SMX is rewritten as,

$$C = \max_{p_{\mathbf{x}_t}}\left(H\left(\mathbf{y}\,|\mathbf{H}\right) - H\left(\mathbf{y}\,|\mathbf{x}_t,\mathbf{H}\right)\right). \qquad (13)$$

An important note from (13) is that the entropy $H(\mathbf{y}\,|\mathbf{x}_t,\mathbf{H})$ does not depend on $\mathbf{x}_t$. Therefore, the maximization in (13) can be reduced to the maximization of $H\left(\mathbf{y}\,|\mathbf{H}\right)$. Taking into account that the distribution that maximizes the entropy is the zero mean complex Gaussian distribution [17], the maximum entropy of $\mathbf{y}$ is,

$$H\left(\mathbf{y}\,|\mathbf{H}\right) = N_r\log_2\left(\pi e\left(\mathbf{H}\mathbf{H}^H + \sigma_n^2\mathbf{I}_{N_r}\right)\right) \qquad (14)$$

Under these conditions and with the help of (13), (14), and (27), the capacity of SMX is given by,

$$C = \log_2\left(\mathbf{I}_{N_r} + \frac{1}{\sigma_n^2}\mathbf{H}\mathbf{H}^H\right) \qquad (15)$$

and the ergodic capacity is,

$$C_{\text{ergodic}} = \mathrm{E}_{\mathbf{H}}\left\{\log_2\left(\mathbf{I}_{N_r} + \frac{1}{\sigma_n^2}\mathbf{H}\mathbf{H}^H\right)\right\} \qquad (16)$$

2) Spatial Modulation: In SM the information bits are modulated in the different constellations symbols and the different channel vectors. Therefore, for SM the capacity in (12) can be re–written as,

$$\begin{aligned} C_{\text{ergodic}} &= \max_{p_{\mathbf{h}_\ell},p_{s_\imath}} I\left(\mathbf{h}_\ell, s_\imath;\mathbf{y}\right), \\ &= \max_{p_{\mathbf{h}_\ell},p_{s_\imath}} \left\{H\left(\mathbf{y}\right) - H\left(\mathbf{y}\,|\mathbf{h}_\ell, s_\imath\right)\right\} \end{aligned} \qquad (17)$$

where $p_{\mathbf{h}_\ell}$ and $p_{s_\imath}$ are the PDFs of $\mathbf{h}_\ell$ and $s_\imath$ respectively.

As in (13) the left hand size of (17) does not depend on $s_\imath$ nor $\mathbf{h}_\ell$. Thus, the maximization in (17) is only of $H\left(\mathbf{y}\right)$. As mentioned before the entropy $H\left(\mathbf{y}\right)$ is maximized when $y \sim \mathcal{CN}\left(0,\sigma_y^2\right)$, with $\sigma_{\mathbf{y}}^2$ denoting the variance of $\mathbf{y}$. From (1), the received signal is complex Gaussian distributed only if $\mathbf{h}_\ell s_\imath \sim \mathcal{CN}\left(\mathbf{0}_{N_r},\mathbf{I}_{N_r}\right)$, where $\mathbf{0}_N$ is an N–length all zeros vector, and $\mathbf{I}_N$ is an $N \times N$ identity matrix.

Assuming $\mathbf{h}_\ell s_\imath$ is complex Gaussian distributed, the entropy of $\mathbf{y}$ following the same steps as discussed for (27) is,

$$H\left(\mathbf{y}\right) = N_r\log_2\left(\pi e\left(1+\sigma_n^2\right)\right). \qquad (18)$$

Under these conditions and with the help of (13), (27), and (18), the space modulation techniques (SMT) capacity is given by,

$$C_{\text{ergodic}} = N_r\log_2\left(1 + 1/\sigma_n^2\right) = N_r\log_2\left(1 + \mathrm{SNR}\right). \qquad (19)$$

Note the capacity in (19) does not depend on the channel. Hence, the capacity in (19) is the ergodic capacity. This is unlike traditional MIMO systems where the capacity depends on the channel, and averaging over the channel is needed to calculate the ergodic capacity, for example SMX in (15) and (16).

From the previous discussion, to achieve the capacity in (19) each element of $\mathbf{h}_{\ell}s_{\imath}$ has to follow a complex Gaussian normal distribution$\sim \mathcal{CN}(0,1)$. Using the product distribution theory [18], the distribution of the used constellations has to be shaped depending on the distribution of the channel so that it solves,

$$\frac{2}{\pi} r e^{-2|r|^2} = \int \frac{1}{|h|} p_s\left(\frac{r}{h}\right) p_h(h)\, dh, \qquad (20)$$

where r denotes the amplitude of each element of $\mathbf{h}_{\ell}s_{\imath}$. Important to note that solving (20) to achieve the channel capacity is the most interesting, but beyond the scope of this paper.

V. Results

A. Capacity Results

The capacity and mutual information performance of SM and SMX for different spectral efficiencies and number of transmit and receive antennas are given in Figs. 1–3. Mutual information simulation results are shown in Fig. 1 for SM and SMX with different number of transmit antennas, $N_t = 2$ and 8, and with $N_r = 8$ and $\eta = 8$. As can be seen from the figure, SM provides an almost identical performance with SMX when $N_t = 8$. However, for $N_t = 2$ SMX provides slightly better performance. This is because the need of higher constellation in SM as compared to SMX. The mutual information for $N_r = 2$ and 8, with $N_t = 8$ and $\eta = 8$ are compared in Fig. 2. It can be seen that both systems have fairly similar performance, even though the constellation size of SM is higher than that of SMX . As expected, the performance of both systems enhances with the increase of the number of receive antennas, where an enhancement of up to 2 bits can be clearly noticed. And SMX indeed offers better performance for the same MIMO setup as compared to SM . However, SM can perform better if the number of transmit antennas increases, which comes at no significant cost since only single radio frequency (RF) chain is needed.

A comparison between simulated mutual information of SM and SMX for different spectral efficiencies ($\eta = 4$, 8, and 12) are depicted in Fig. 3, with $N_t = N_r = 4$. The theoretical channel capacity for SM and SMX are also shown. It can be seen that for low spectral efficiencies 4 and 8 bits, SM and SMX have almost the same performance. Yet, for $\eta = 12$ bits, SMX offers higher mutual information than SM. Besides, it can be seen that at SNR= 8 dB, SM capacity is 7.4 bits higher than the capacity of SMX. Thus and even though SMX outperforms SM, SM can achieve a capacity that is higher than the capacity of SMX. However, to achieve such capacity, the considered constellation symbols has to be properly shaped depending on the MIMO channel statistics so it solves (20). Hence, solving (20) is of a great interest as it promises a great extension to the existing MIMO capacity. Though, designing such constellation symbols is mathematically involved and we hope to address it in our, and we hope others, future research.

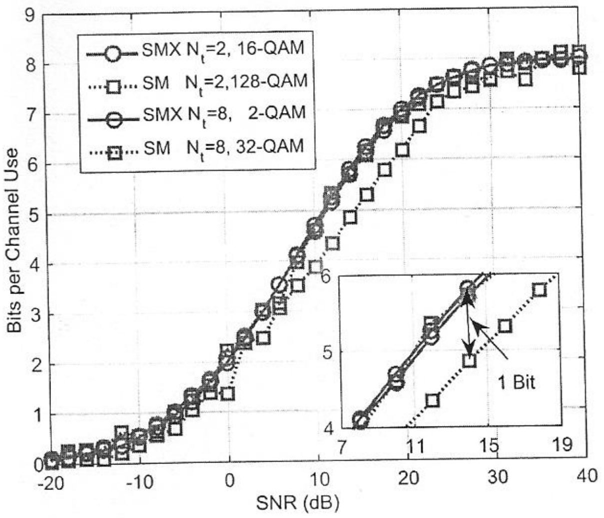

Fig. 1. Comparison between the mutual information of SM and SMX for different N_t, where $\eta = 8$, $N_t = 2$ and 8 and $N_r = 8$. (Circle marker) SMX, (Square marker) SM ,(blue color)$N_r = 2$, and (red color)$N_r = 8$.

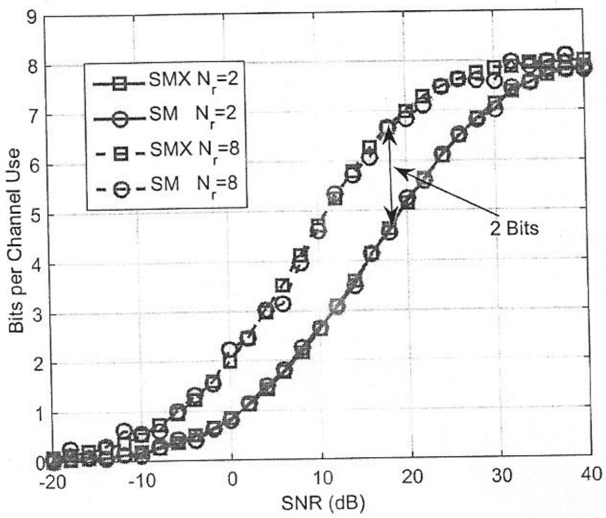

Fig. 2. Comparison between the mutual information of SM and SMX for different N_r where $\eta = 8$, $N_t = 8$ and $N_r = 2, 8$.(Circle marker) SM, (Square marker) SMX ,(Solid line)$N_r = 2$, and (Dashed line)$N_r = 8$.

B. Energy Efficiency

This section presents a comparison between the EE of SM and SMX for different antenna setups. The EE could simply be defined as the ratio between the total number of bits that can be transmitted by a system without any errors (C) to the total consumed power by the system (P_s),

$$EE = \frac{C_{\text{ergodic}}}{P_s} \qquad (21)$$

The EARTH power model is used for the comparison, which describes the relation between the total power supplied or consumed by a transceiver system and the RF transmit power

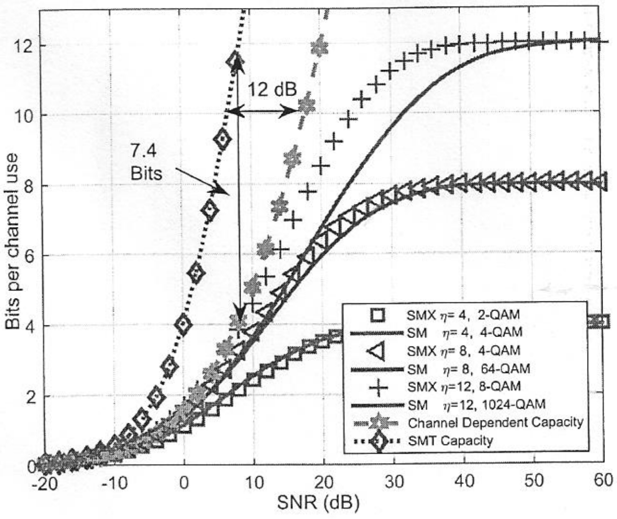

Fig. 3. The capacity of SM and SMX compared to the simulated mutual information of SM and SMX over mmWave channel for different spectral efficiency, where $\eta = 4, 8$ and 12, and $N_t = N_r = 4$. (Dashed line and Diamond marker) SM Capacity,(Dashed line and cross marker) Channel dependent capacity.(Full line)SM, (Plus marker) SMX $\eta = 12$, (Arrow marker) SMX $\eta = 8$ and (Square marker) SMX $\eta = 4$.

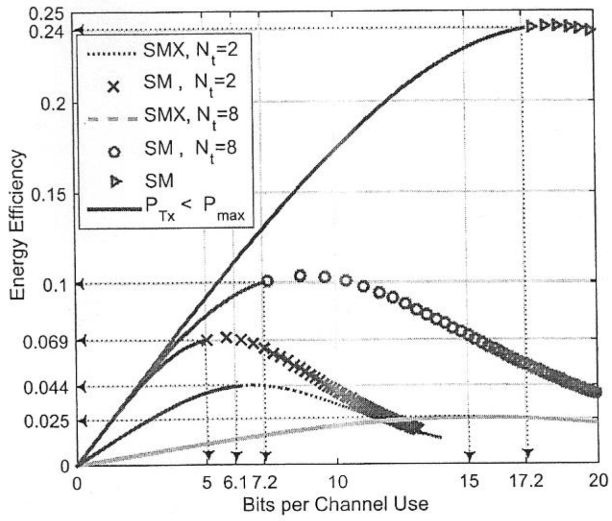

Fig. 4. EE for Micro BS scenario with $N_r = 4$, (Dotted line) SMX with $N_t = 2$, (Dashed line) SMX with $N_t = 8$, (Cross Marker) SM with $N_t = 2$, (Circle marker) SM with $N_t = 8$, (Arrow marker) EE of SM w.r.t channel independent capacity. (Solid line) when $(P_{Tx} \leqslant P_{max})$ for all scenario of SM and SMX.

as:

$$P_s = N_{RF} P_{min} + m P_{Tx} \tag{22}$$

where N_{RF} is the number of the used RF chains, $N_{RF} = Nt$ for SMX and $N_{RF} = 1$ for SM P_{min} is the minimum consumed power per RF chain, m denotes the slope of the load dependent power consumption, and P_{Tx} is the total RF transmit power.

Fig. 4 shows a comparison between the energy efficiency of SM and SMX with respect to ergodic capacity. In addition, the EE for SM in term of the channel independent capacity (19) also considered in the comparison. The simulation results based on the recent real-world measurements which were carried on a microcell environment in [9]. From [6] for micro cell base stations (BSs), $P_{min} = 53$ w, $m = 3.1$, and the maximum transmit power per RF chain is $P_{max} = 6.3$w are considered.

For $P_{Tx} \leqslant P_{max}$, it could be seen from the figure that SM offers better EE than SMX . Where the obtained results show that SM can improve the EE by 36% and 74% compared to SMX for $N_t = 2$ and $N_t = 8$, respectively. This could be explained by equation (22), where the total RF transmit power for SM is one, but for SMX it increases by increasing the number of transmit antennas, as for SMX the number of RF chains used is equal to the number of transmit antennas. For this reason, having several transmit antennas improves the EE of the SM system unlike for SMX . For example, SM with $Nt = 8$ is 45% more energy efficient compared to SM with $Nt = 2$. While SMX for $N_t = 8$ is less energy efficient ,by 43%, than SMX with $Nt = 2$.

VI. Conclusions

In this paper, a comparison between the capacity and EE of SM and SMX systems over 3D mmWave outdoor channel model is studied and presented. It is disclosed that the theoretical capacity of SM is higher than that of SMX. However,this is only achieved with proper design of signal constellations. Using ordinary constellation symbols the simulation results show that SMX offers better mutual information performance compared to SM. On the other hand, as expected, the EE obtained results show that SM is more energy efficient than SMX , where SM uses only one RF chain. In addition, maximizing the EE could be achieved if a proper design of the constellation symbol is considered.

Appendix A
Derrivation of $I(\mathrm{x}_t; \mathrm{y}|\mathbf{H})$ in (9)

Firstly, derive $H(\mathrm{y})$,

$$\begin{aligned} H(\mathrm{y}|\mathbf{H}) &= -\int_{\mathrm{y}} p_{\mathrm{y}|\mathbf{H}}(\mathrm{y}) \log_2 p_{\mathrm{y}|\mathbf{H}}(\mathrm{y})\, dy \\ &= -\mathrm{E}_{\mathrm{y}} \left\{ \log_2 p_{\mathrm{y}|\mathbf{H}}(\mathrm{y}) \right\}, \end{aligned} \tag{23}$$

where $p_{\mathrm{y}|\mathbf{H}}(\cdot)$ is the PDF of the received vector y knowing $\mathbf{H}$, and it is given by,

$$\begin{aligned} p_{\mathrm{y}|\mathbf{H}} &= \int_{\mathrm{x}_t} p_{\mathrm{x}_t}(\mathrm{x}_t)\, p_{(\mathrm{y}|\mathrm{x}_t,\mathbf{H})}(\mathrm{y})\, d\mathrm{x}_t \\ &= \frac{1}{(\pi\sigma_n^2)^{N_r}} \frac{1}{\eta} \sum_{\mathrm{x}_t \in \mathcal{Q}} e^{\frac{-\|\mathrm{y}-\mathbf{H}\mathrm{x}_t\|_F^2}{\sigma_n^2}}, \end{aligned} \tag{24}$$

where $p_{(\mathrm{y}|\mathrm{x}_t,\mathbf{H})}$ is the PDF of the received vector y knowing the transmitted vector x_t, and the channel $\mathbf{H}$, and it is given by,

$$p_{(\mathbf{y}|\mathbf{x}_t,\mathbf{H})}(\mathbf{y}) = \frac{1}{(\pi\sigma_n^2)^{N_r}} e^{\frac{-\|\mathbf{y}-\mathbf{H}\mathbf{x}_t\|_F^2}{\sigma_n^2}}. \quad (25)$$

From (23) and (24), the entropy of $\mathbf{y}$ is,

$$H(\mathbf{y}|\mathbf{H}) = \log_2 \eta + N_r \log_2 \left(\pi\sigma_n^2\right) - \mathrm{E}_{\mathbf{y}} \left\{ \log_2 \sum_{\mathbf{x}_t \in \mathcal{Q}} e^{\frac{-\|\mathbf{y}-\mathbf{H}\mathbf{x}_t\|_F^2}{\sigma_n^2}} \right\}. \quad (26)$$

Secondly, the entropy of $\mathbf{y}$ knowing $\mathbf{x}_t$ is,

$$\begin{aligned} H(\mathbf{y}|\mathbf{x}_t, \mathbf{H}) &= -\mathrm{E}_{\mathbf{y}} \left\{ \log_2 p_{\mathbf{y}|\mathbf{x}_t}(\mathbf{y}|\mathbf{x}_t) \right\} \\ &= -\mathrm{E}_{\mathbf{n}} \left\{ \log_2 p_{\mathbf{n}}(\mathbf{n} + \mathbf{H}\mathbf{x}_t) \right\} \\ &= N_r \log_2 \left(\pi\sigma_n^2 e\right). \quad (27) \end{aligned}$$

where $p_{\mathbf{n}}$ is the PDF of the noise vector $\mathbf{n}$. Note, from [19] the entropy of an N length complex Guassian random vector with mean u and variance σ is $N\log_2(\pi\sigma e)$.

Finally, substituting (26) and (27), in (8) lead to $I(\mathbf{x}_t;\mathbf{y})$ given in (9).

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