Efficient Signaling Schemes for mmWave LOS MIMO Communication Using Uniform Linear and Circular Arrays

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Abstract—**High spatial correlation in line-of-sight multiple-input multiple-output (LOS MIMO) channels in mmWave communication is a cause for the channel matrices to have low rank. However, with proper placement of the transmit and receive antennas, the channel matrix can be made full/high rank. While optimum placements for full rank can be realized with uniform linear arrays (ULA), this may not be the case with uniform circular arrays (UCA). This motivates the need to investigate efficient signaling schemes for LOS MIMO schemes for different array configurations. Accordingly, in this work, we study various signaling schemes including spatial multiplexing (SMP), spatial modulation (SM), and generalized spatial modulation (GSM) in the context of both ULA and UCA. Our analytical and simulation results show that GSM achieves better performance compared to SMP and SM. We also propose a new signaling scheme, termed as *subarray index modulation (SAIM)* scheme, where groups of antennas in the array (subarrays) are indexed to convey information bits and each antenna within an activated subarray carries an independent modulation symbol. It is found that the proposed SAIM scheme can achieve better performance compared to SMP, SM, and GSM schemes.**

Keywords *– mmWave communications, LOS MIMO, linear array, circular array, spatial modulation, subarray index modulation.*

I. INTRODUCTION

The demand for high data rates, availability of 7 GHz of unlicensed spectrum around 60 GHz, and rapid advancement of low cost CMOS millimeter wave (mmWave) integrated circuits have motivated the design of wireless links that operate in the mmWave frequencies [1]. The mmWave propagation in typical indoor/outdoor environments is dominated by the line-of-sight component. Also, the small wavelengths in mmWave transmissions allow the use of a large number of antenna elements in a given aperture, leading to the feasibility of designing line-of-sight multiple-input multiple output (LOS MIMO) systems. An issue in such systems is the high spatial correlation in the LOS MIMO channels that can result in low rank channel matrices. However, it has been shown that through proper placement of the transmit and receive antennas, the rank of the channel can be increased [2], [3]. In particular, in uniform linear arrays (ULA), optimum placement of antennas can result in the channel matrix being orthogonal [3]. However, in uniform circular arrays (UCA), optimum placement can result in orthogonal channel matrix only for arrays with 3 or 4 antennas [4].

Spatial multiplexing (SMP) and beamforming (BF) are popular signaling approaches in LOS MIMO systems [6], [7]. Another attractive signaling approach for LOS MIMO systems is spatial modulation (SM) [8]. The basic version of SM uses only one radio frequency (RF) chain and multiple antennas at the transmitter. Only one antenna is activated at a time, and a modulation symbol is sent on the activated antenna. The choice of the antenna to be activated is made based on additional information bits. A more generalized version, called generalized SM (GSM), uses more than one RF chain and activates multiple antennas simultaneously. Independent symbols are sent simultaneously on the activated antennas, and the choice of the active antennas is made based on additional information bits [9]. Recent works in [10], [11], [12] have investigated space shift keying (SSK, which is a special case of SM), SM, and GSM in LOS MIMO. These works, however, consider only ULA. Given that placement which achieves orthogonality of channel matrix for more than four antennas is infeasible in UCA [4], it becomes important to investigate efficient signaling schemes for UCA. Accordingly, our first contribution in this paper is to study the performance of SM based signaling techniques in the context of both ULA and UCA in comparison with conventional SMP. We derive analytical upper bounds on the bit error rate (BER) performance of these signaling schemes in LOS MIMO systems. Analytical and simulation results are found to closely match at moderate-to-high SNRs. Numerical results show that GSM can achieve better performance compared to SMP and SM in ULA as well as UCA. Our second contribution in this paper is that we propose a new signaling scheme that groups antennas into subarrays and exploits indexing of these subarrays to convey additional information bits, while each antenna within a subarray sends an independent modulation symbol. We call this proposed scheme as *subarray index modulation (SAIM)*. Numerical results show that the proposed SAIM scheme can outperform SMP, SM, and GSM schemes.

II. LOS MIMO SYSTEM MODEL

Consider an LOS MIMO system with N_t and N_r antennas at the transmitter and receiver arrays, respectively. We consider uniform linear and circular arrays (ULA and UCA). Let $\mathbf{H}$ denote the $N_r \times N_t$ LOS MIMO channel matrix. Assuming perfect synchronization, the $N_r \times 1$ received signal vector at the receiver is given by

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

where $\mathbf{y} \in \mathbb{C}^{N_r}$ is the received signal vector, $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix, $\mathbf{x} \in \mathbb{C}^{N_t}$ is the transmitted signal vector, and $\mathbf{n} \sim \mathcal{CN}(0, \sigma^2\mathbf{I})$ is the additive white Gaussian noise vector. The entry in the ith row and jth column of $\mathbf{H}$, denoted by h_{ij}, is the gain of the LOS path between the jth transmit antenna and ith receive antenna. Let D denote the distance between the transmit and receive arrays, and d_{ij} denote the LOS path length between the jth transmit antenna and ith receive antenna. Then, by Friis transmission equation, h_{ij} can be written as [10]

$$h_{ij} \; = \; \frac{\lambda}{4\pi d_{ij}} e^{-jkd_{ij}} \frac{4\pi D}{\lambda} \; \approx \; e^{-jkd_{ij}}, \tag{2}$$

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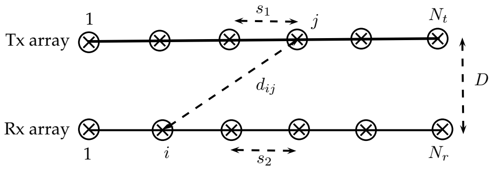

Fig. 1. LOS MIMO system with uniform linear arrays.

where $k = \frac{2\pi}{\lambda}$, λ is the wavelength, and the approximation is because of the very small relative path loss differences. So $\mathbf{H}$ is deterministic and it depends only on the distances between the transmit and receive antennas and the wavelength.

A. *Condition number of* $\mathbf{H}$ *in ULA*

An LOS MIMO system with ULA at the transmitter and receiver is shown in Fig. 1. The inter-antenna spacing at the transmitter and receiver are denoted by s_1 and s_2, respectively. The rank of the channel matrix $\mathbf{H}$ depends on the parameters s_1, s_2, D, and λ. High rank can be achieved through proper choice of these parameters (i.e., through proper placement of the antennas). The matrix $\mathbf{H}$ can be full rank if the condition

$$\langle \mathbf{h}_i, \mathbf{h}_j \rangle = 0, \forall i \neq j \tag{3}$$

is satisfied, where $\mathbf{h}_i$ denotes the ith column of $\mathbf{H}$. It has been shown that the optimum placement that satisfies the above condition for ULA satisfies the following relation [3]:

$$s_1 s_2 \approx \frac{(2n+1)D\lambda}{N_r}, \quad n \in \mathbb{Z}^+. \tag{4}$$

For placements satisfying (4), $\mathbf{H}$ becomes orthogonal, i.e., all the singular values are equal and the condition number is one. Figure 2 shows the condition number of $\mathbf{H}$ as a function of antenna spacing s, where we have taken $s_1 = s_2 = s$, for $N_t = N_r = 4, 8$ at 60 GHz and $D = 3$m. It can be seen that condition number one is achieved at optimum spacings.

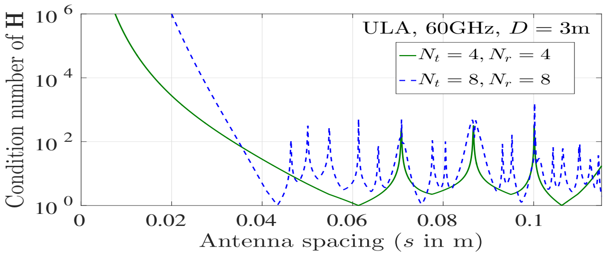

Fig. 2. Condition number of $\mathbf{H}$ versus antenna spacing ($s_1 = s_2 = s$) for 4×4 and 8×8 ULA at 60 GHz and $D = 3$m

B. *Condition number of* $\mathbf{H}$ *in UCA*

Circular array is another practically useful array configuration. A uniform circular array has antenna elements placed in a circular arrangement with uniform angular separation. An LOS MIMO system with UCA at the transmitter and receiver is shown in Fig. 3. The radii of the transmit and receive antenna arrays are assumed to be the same, denoted by r. The distance between transmit and receive arrays is denoted by D. The angular separation between antenna elements will be $\frac{2\pi}{N_t}$ and $\frac{2\pi}{N_r}$ for the transmit and receive arrays, respectively. The distance between the jth transmit and ith receive antennas is denoted by d_{ij}.

Note that UCA with $N_t = N_r = 2$ can be viewed to be the same as ULA with $N_t = N_r = 2$. It has been shown in [4] that for $N_t = N_r = 3, 4$, the r which satisfies the condition in (3) is given by

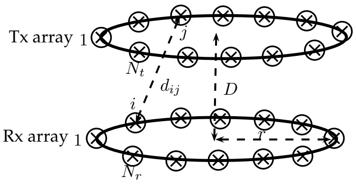

Fig. 3. LOS MIMO system with uniform circular arrays.

$$r = \sqrt{\frac{\lambda D}{2N \sin^2(\theta/2)}}, \tag{5}$$

where $N = N_t = N_r$ and $\theta = \frac{2\pi}{N}$. Whereas, the full rank condition is not satisfied for $N > 4$ [4], and therefore the condition number will be grater than one for $N > 4$. These are illustrated in Fig. 4. It can be seen that while condition number one is achieved in UCA with $N_t = N_r = 4$ at optimum r, it is not the case for $N_t = N_r = 8$. Indeed, the condition number is greater than one for all r making the 8×8 UCA to have non-zero spatial correlation even for the best r that achieves the minimum condition number. This then motivates the need to assess the efficacy of different signaling schemes for different array configurations in LOS MIMO. In the next sections, we study MIMO signaling schemes in the context of both ULA and UCA and propose new signaling schemes.

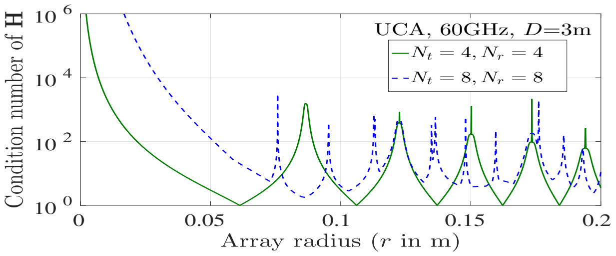

Fig. 4. Condition number $\mathbf{H}$ versus antenna array radius r for 4×4 and 8×8 UCA at 60 GHz and $D = 3$m.

III. SMP, SM, GSM SIGNALING IN ULA AND UCA

We consider the following signaling schemes in LOS MIMO with ULA and UCA: *i*) SMP, *ii*) SM, and *iii*) GSM.

i) *SMP:* SMP uses N_t antennas and N_t RF chains at the transmitter. All the antennas are activated simultaneously in a given channel use. N_t symbols from a modulation alphabet $\mathbb{A}$ are transmitted in a channel use. So the transmission efficiency in SMP is $\eta_{\text{smp}} = N_t \log_2 |\mathbb{A}|$ bits per channel use (bpcu).

ii) *SM:* SM also uses N_t antennas but only one RF chain at the transmitter. It uses one among the N_t antennas to transmit in a given channel use. The antenna to transmit is chosen based on $\log_2 N_t$ information bits. The chosen antenna transmits a symbol from a modulation alphabet $\mathbb{A}$. So the transmission efficiency in SM is $\eta_{\text{sm}} = \log_2 N_t + \log_2 |\mathbb{A}|$ bpcu. Let $\mathbf{x} \in \mathbb{S}_{N_t,\mathbb{A}}$ denote the $N_t \times 1$ transmitted signal vector belonging to the SM signal set $\mathbb{S}_{N_t,\mathbb{A}}$. Then, $\mathbf{x}$ will have an $|\mathbb{A}|$-ary modulation symbol in one of the coordinates and zeros in all other coordinates. The SM signal set for an N_t transmit antenna system can be written as

$$\begin{aligned} &\mathbb{S}_{N_t,\mathbb{A}} = \{\mathbf{x}_{j,l} : j = 1, \cdots, N_t, l = 1, \cdots, |\mathbb{A}|\}, \\ &\text{s.t } \mathbf{x}_{j,l} = [0, \cdots, 0, \underbrace{x_l}_{j\text{th coordinate}}, 0, \cdots, 0]^T, x_l \in \mathbb{A}. \end{aligned} \tag{6}$$

iii) GSM: GSM uses N_t antennas and N_{rf}, $1 \leq N_{rf} \leq N_t$, RF chains at the transmitter. N_{rf} out of N_t transmit antennas are chosen in a channel use based on $\lfloor \log_2 \binom{N_t}{N_{rf}} \rfloor$ information bits, and N_{rf} independent symbols from a modulation alphabet $\mathbb{A}$ are sent on these selected antennas [9]. The remaining $N_t - N_{rf}$ antennas remain silent (i.e., they can be viewed as transmitting the symbol 0). So the transmission efficiency of GSM is given by $\eta_{\text{gsm}} = \lfloor \log_2 \binom{N_t}{N_{rf}} \rfloor + N_{rf} \log_2 |\mathbb{A}|$ bpcu. An antenna activation pattern (AAP) is an N_t-length vector that indicates which antennas are active. There are $L = \binom{N_t}{N_{rf}}$ AAPs possible and $2^{\lfloor \log_2 \binom{N_t}{N_{rf}} \rfloor}$ among them are adequate for signaling. These patterns form a set called the AAP set, denoted by $\mathbb{U}$. The GSM signal set, $\mathbb{S}^{N_{rf}}_{N_t,\mathbb{A}}$, can be written as

$$\mathbb{S}^{N_{rf}}_{N_t,\mathbb{A}} = \{\mathbf{x} | \mathbf{x} \in \mathbb{A}_0^{N_t \times 1}, \|\mathbf{x}\|_0 = N_{rf}, \mathbf{t}^{\mathbf{x}} \in \mathbb{U}\}, \qquad (7)$$

where $\mathbb{A}_0 \triangleq \mathbb{A} \cup 0$, $\|\mathbf{x}\|_0$ denotes the number of non-zero entries in $\mathbf{x}$, and $\mathbf{t}^{\mathbf{x}}$ denotes the AAP vector corresponding to $\mathbf{x}$, where $t^{\mathbf{x}}_j = 1$ iff $x_j \neq 0, \forall j \neq 1, 2, \cdots, N_t$.

A. BER performance analysis

Here, we derive an upper bound on the BER performance of maximum likelihood (ML) detection for SMP, SM, and GSM. The ML detection rule for the considered LOS MIMO system model is given by

$$\hat{\mathbf{x}} = \underset{\mathbf{x} \in \mathbb{S}}{\text{argmin}} \, \|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2, \qquad (8)$$

where $\mathbb{S}$ denotes the signal set of interest (i.e., one of SMP, SM, GSM signal sets).

Upper bound on BER: The ML detection rule in (8) can be written as

$$\hat{\mathbf{x}} = \underset{\mathbf{x} \in \mathbb{S}}{\text{argmin}} \left(\|\mathbf{H}\mathbf{x}\|^2 - 2\mathbf{y}^T \mathbf{H}\mathbf{x} \right). \qquad (9)$$

Assuming that $\mathbf{H}$ is known at the receiver, the pairwise error probability (PEP) that the receiver decides in favor of the signal vector $\mathbf{x}_2$ when $\mathbf{x}_1$ was transmitted can be written as

$$\begin{aligned} PEP &= PEP(\mathbf{x}_1 \to \mathbf{x}_2 | \mathbf{H}) \\ &= P\left(2\mathbf{y}^T \mathbf{H}(\mathbf{x}_2 - \mathbf{x}_1) > (\|\mathbf{H}\mathbf{x}_2\|^2 - \|\mathbf{H}\mathbf{x}_1\|^2)\right) \\ &= P\left(2\mathbf{n}^T \mathbf{H}(\mathbf{x}_2 - \mathbf{x}_1) > \|\mathbf{H}(\mathbf{x}_2 - \mathbf{x}_1)\|^2\right). \qquad (10) \end{aligned}$$

Define $g \triangleq 2\mathbf{n}^T \mathbf{H}(\mathbf{x}_2 - \mathbf{x}_1)$. It can be seen that g is a Gaussian r. v. with mean zero and variance $2\sigma^2 \|\mathbf{H}(\mathbf{x}_2 - \mathbf{x}_1)\|^2$. Therefore, we can write

$$PEP = Q\left(\frac{\|\mathbf{H}(\mathbf{x}_2 - \mathbf{x}_1)\|}{\sqrt{2}\sigma}\right), \qquad (11)$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{\frac{-t^2}{2}} dt$. Defining $K \triangleq |\mathbb{S}|$, an upper bound on the BER for ML detection can be obtained using union bound as

$$\begin{aligned} BER &\leq \frac{1}{\eta K} \sum_{i=1}^{K} \sum_{j=1, j \neq i}^{K} d_H(\mathbf{x}_i, \mathbf{x}_j) PEP(\mathbf{x}_i \to \mathbf{x}_j | \mathbf{H}) \\ &= \frac{1}{\eta K} \sum_{i=1}^{K} \sum_{j=1, j \neq i}^{K} d_H(\mathbf{x}_i, \mathbf{x}_j) Q\left(\frac{\|\mathbf{H}(\mathbf{x}_i - \mathbf{x}_j)\|}{\sqrt{2}\sigma}\right), \qquad (12) \end{aligned}$$

where $d_H(\mathbf{x}_i, \mathbf{x}_j)$ is the Hamming distance between the bit mappings corresponding to the vectors $\mathbf{x}_i$ and $\mathbf{x}_j$, and η is the transmission efficiency of the signaling scheme of interest.

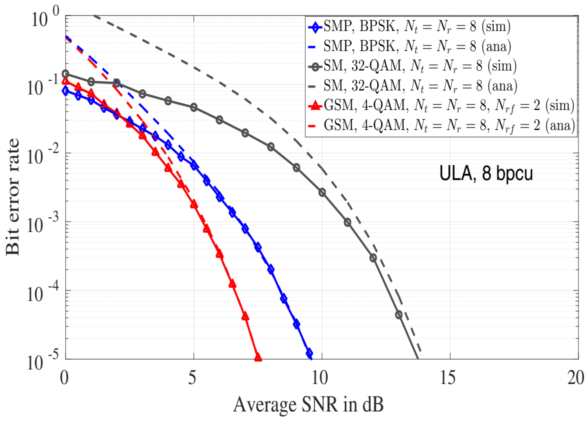

Fig. 5. BER of SMP, SM, and GSM in LOS MIMO systems with ULA operating at 60 GHz with $N_t = N_r = 8$, $D = 3$m, $s = 43.3$mm, 8 bpcu.

B. Results and discussion

Here we present the analytical and simulation results of the BER performance of SMP, SM, and GSM for ULA and UCA.

1) SMP, SM, GSM performance with ULA: In Fig. 5, we plot the BER of SMP, SM, and GSM with 8 bpcu for ULA. In all the three systems, the antennas are placed such that the resulting channel matrix has a condition number equal to one. From Fig. 2, the smallest spacing between the antenna elements for which a channel matrix with condition number one is achieved is 43.3mm. The BER performance is studied with this spacing. All the three schemes use 8 Tx and 8 Rx antennas. SMP uses BPSK, SM uses 32-QAM, and GSM uses 4-QAM and $N_{rf} = 2$. Analytical bounds are found be tight at moderate-to-high SNRs. Also, from the plots, we see that GSM has a better performance compared to SMP and SM. The reason can be explained as follows. In SMP, all the N_t antennas transmit symbols and hence there exists interference among the data streams. Interference of symbols transmitted from different antennas does not exist in SM as only one transmit antenna is active in a given channel use. However, for a given number of antennas, SM requires to use a higher-order QAM to achieve higher spectral efficiencies. This will degrade the performance of SM. In this case, SM requires 32-QAM to achieve 8 bpcu. Hence the performance of SM degrades. GSM uses fewer RF chains compared to SMP. This has the advantage of lesser interference in GSM. Also, since more information bits are conveyed through antenna indexing, GSM requires a smaller QAM size compared to SM. Hence, GSM outperforms both SMP and SM.

2) SMP, SM, GSM performance with UCA: In Fig. 6, we plot the BER of SMP, SM, and GSM with 8 bpcu for UCA, for the same configuration described above for ULA. In all the three systems, the array radius is such that the resulting channel matrix has minimum condition number. A condition number less than 10 is acceptable in practice [13]. From Fig. 4, the smallest array radius for which a channel matrix with a condition number less than 10 is achieved is 72.89mm. The BER performance for UCA is studied with this radius. In Fig. 6, the analytical bounds are found to be tight at moderate-to-high SNRs. We observe that here also GSM has a better performance compared to SMP and SM. Note that GSM achieves this better performance with only 2 RF chains compared to 8 RF chains in SMP. The improvement in the

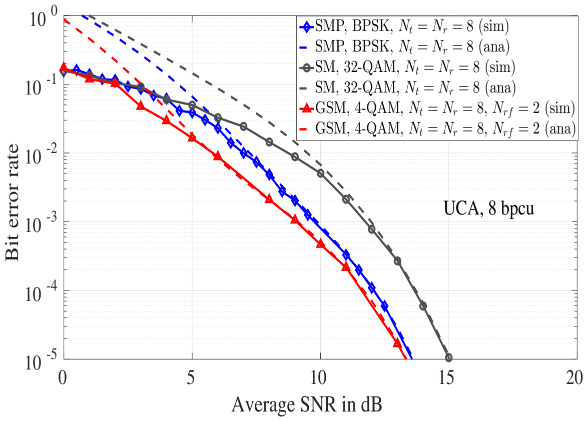

Fig. 6. BER of SMP, SM, and GSM in LOS MIMO systems with UCA operating at 60 GHz with $N_t = N_r = 8$, $D = 3$m, $r = 72.89$mm, 8 bpcu.

performance of GSM over the performance of SMP is small compared to that in ULA. The reason can be explained as follows. In a UCA with 8 Tx and 8 Rx antennas, even with a best possible radius, the condition number of the channel matrix is not equal to one. Hence, there exists correlation between the MIMO subchannels. The index bits degrade when the channel is correlated. Hence the performance of GSM shows a smaller improvement compared to the performance of SMP. This can be alleviated using the subarray indexing scheme we propose in the following section.

IV. PROPOSED SUBARRAY INDEX MODULATION

In the proposed SAIM scheme, the transmit antenna array with N_t antennas is divided into N_s subarrays, each subarray consisting of $N_a = \frac{N_t}{N_s}$ antennas. The SAIM transmitter is shown in Fig. 7. In a given channel use, k subarrays out of N_s subarrays are chosen based on $\lfloor \log_2 \binom{N_s}{k} \rfloor$ bits. The chosen subarrays are activated and each antenna in the activated subarrays carries an independent modulation symbol. The antennas in the remaining $N_s - k$ subarrays remain silent. So, in a channel use, kN_a antennas transmit symbols simultaneously from a modulation alphabet $\mathbb{A}$. Therefore, the transmission efficiency of SAIM is given by $\eta_{\text{saim}} = \lfloor \log_2 \binom{N_s}{k} \rfloor + kN_a \log_2 |\mathbb{A}|$ bpcu. A subarray activation pattern (SAP) is an N_s-length vector that indicates which subarrays are active such that the ith element in the vector is a 1 if the ith subarray is activated and 0 otherwise. There are $\binom{N_s}{k}$ SAPs possible out of which $2^{\lfloor \log_2 \binom{N_s}{k} \rfloor}$ are adequate for signaling. These patterns form a set called the SAP set, denoted by $\mathbb{P}$. The SAIM signal set, $\mathbb{S}^k_{N_t,N_s,\mathbb{A}}$, can then be written as

$$\begin{aligned} \mathbb{S}^k_{N_t,N_s,\mathbb{A}} = \{ & \mathbf{x} : \mathbf{x} \in \mathbb{A}_0^{N_t}, \ \mathbf{x} = [\mathbf{s}_1^T, \mathbf{s}_2^T, \cdots, \mathbf{s}_{N_s}^T]^T, \\ & \|\mathbf{x}\|_0 = kN_a, \ \mathbf{s}_i \in \mathbb{A}^{N_a} \text{ if } t_i^{\mathbf{x}} = 1, \\ & \mathbf{s}_i \in \mathbf{0}^{N_a} \text{ if } t_i^{\mathbf{x}} = 0, \ i = 1, \cdots, N_s \}, \end{aligned} \tag{13}$$

where $\mathbb{A}_0 \triangleq \mathbb{A} \cup 0$, $\|\mathbf{x}\|_0$ denotes the number of non-zero entries in $\mathbf{x}$, $\mathbf{s}_i$ denotes the symbol vector corresponding to the ith subarray, $\mathbf{t}^{\mathbf{x}} \in \mathbb{P}$ is the SAP vector corresponding to the transmit vector $\mathbf{x}$, $\|\mathbf{t}^{\mathbf{x}}\|_0 = k$, and $t_i^{\mathbf{x}}$ denotes the ith element of $\mathbf{t}^{\mathbf{x}}$.

Example: Consider $N_t = 4$, $N_s = 2$, $N_a = 2$, $k = 1$, and BPSK. For this setting, $\eta_{\text{saim}} = \log_2 2 + 2\log_2 2 = 3$ bpcu. The SAP vector set $\mathbb{P}$ is given by $\mathbb{P} = \{[1 \ 0]^T, \ [0 \ 1]^T\}$, and the SAIM signal set is given by

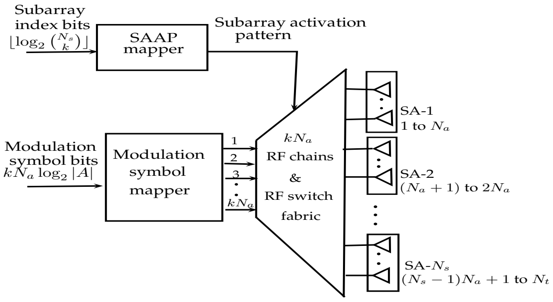

Fig. 7. Subarray index modulation transmitter.

$$\mathbb{S}^k_{N_t,N_s,\mathbb{A}} = \left\{ \begin{bmatrix}1\\1\\0\\0\end{bmatrix}, \begin{bmatrix}1\\-1\\0\\0\end{bmatrix}, \begin{bmatrix}-1\\1\\0\\0\end{bmatrix}, \begin{bmatrix}-1\\-1\\0\\0\end{bmatrix}, \begin{bmatrix}0\\0\\1\\1\end{bmatrix}, \begin{bmatrix}0\\0\\1\\-1\end{bmatrix}, \begin{bmatrix}0\\0\\-1\\1\end{bmatrix}, \begin{bmatrix}0\\0\\-1\\-1\end{bmatrix} \right\}.$$

The ML detection rule for SAIM in the considered LOS system model is given by

$$\hat{\mathbf{x}} = \underset{\mathbf{x} \in \mathbb{S}^k_{N_t,N_s,\mathbb{A}}}{\text{argmin}} \ \|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2. \tag{14}$$

A. *Results and discussions*

In this subsection, we present BER performance comparisons between the proposed SAIM scheme and other modulation schemes. In Fig. 8, we plot the BER of SMP, SM, GSM, and SAIM with 8 bpcu and UCA for the same settings described in Sec. III-B2. In SAIM, $N_t = 8$ Tx antennas are divided into $N_s = 4$ subarrays each having $N_a = 2$ antennas. One out of the 4 subarrays (i.e., $k = 1$) is chosen and 8-QAM symbols are sent on the antennas in the chosen subarray. As in Sec. III-B2, the UCA radius is set at 72.89mm.

From the plots in Fig. 8, we see that SAIM and GSM perform better than SMP and SM. Also, GSM performs better at low SNRs and SAIM performs better at moderate-to-high SNRs. This performance crossover between SAIM and GSM can be explained by taking a look at 1) the contribution of index bit errors and QAM bit errors to the overall BER, and 2) the normalized minimum Euclidean distance between any two vectors $\mathbf{H}\mathbf{x}_1$ and $\mathbf{H}\mathbf{x}_2$ ($d_{min,\mathbf{H}}$). For this purpose, in Fig. 9, we individually plot the simulated index BER, QAM BER, and overall BER of SAIM and GSM for the LOS MIMO system setting in Fig. 8. We see in Fig. 9 that the overall BER in SAIM is dominated by the poor performance of QAM BER (because of 8-QAM) though its index BER is good. Since GSM uses only 4-QAM, its QAM BER and overall BER are better than those of SAIM at low SNRs. This explains the better performance of GSM at low SNRs. At high SNRs, however, the performance is determined by the $d_{min,\mathbf{H}}$. For the considered system setting, SAIM has a larger $d_{min,\mathbf{H}}$ value of 0.4471 compared to the GSM $d_{min,\mathbf{H}}$ value of 0.3921. This better minimum distance makes SAIM to perform better than GSM in moderate-to-high SNRs.

Next, in Fig. 10, we present a performance comparison between SAIM and GSM for 8×8 UCA with 10 bpcu. While SAIM uses $N_t = 8$, $N_s = 4$, $N_a = 2$, $k = 1$, $kN_a = 2$, and 16-QAM to achieve 10 bpcu, GSM uses $N_t = 8$, $N_{rf} = 2$, and 8-QAM to achieve the same bpcu. Another performance comparison is presented in Fig. 11 for 6×6 UCA with $r = 68.59$mm and 7 bpcu. In Fig. 11 SAIM uses $N_t = 6$, $N_s = 2$, $N_a = 3$, $k = 1$, $kN_a = 3$, and 4-QAM to achieve

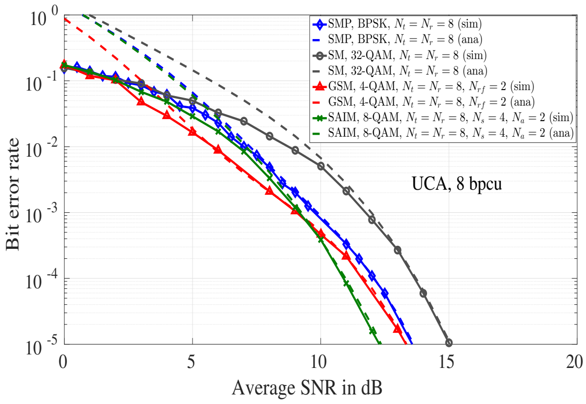

Fig. 8. BER of SMP, SM, GSM, and SAIM in LOS MIMO systems with UCA at 60 GHz with $N_t = N_r = 8$, $D = 3$m, $r = 72.89$mm, 8 bpcu.

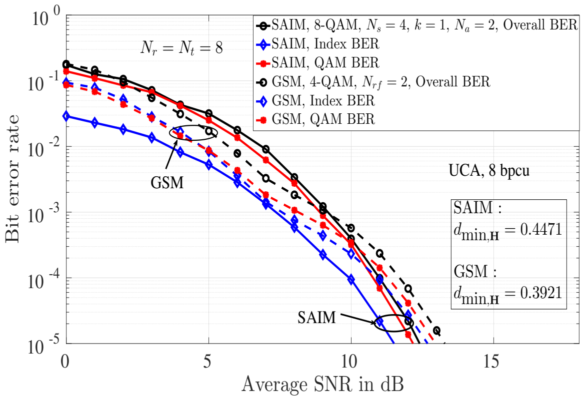

Fig. 9. Plots of index bits BER, QAM bits BER, and overall BER of GSM and SAIM for the LOS MIMO system in Fig. 8.

7 bpcu, and GSM uses $N_t = 6$, $N_{rf} = 3$, and BPSK to achieve the same bpcu. From Figs. 10 and 11, we observe that the proposed SAIM achieves better $d_{min,\mathbf{H}}$ and BER performance compared to GSM. The above results indicate that the proposed SAIM approach provides an efficient and flexible way to map bits through subarray indexing which can achieve good signal distance properties and performance in mmWave LOS MIMO systems.

V. CONCLUSIONS

We investigated spatial modulation (SM) based techniques in the context of mmWave LOS MIMO systems. SM based signaling schemes are attractive for mmWave LOS MIMO communication as they can use fewer transmit RF chains that can lead to reduced hardware complexity and cost. We first studied SMP, SM, and GSM signaling schemes in the context of both ULA and UCA. Efficient signaling schemes for UCA is important because of the infeasibility of full rank antenna placements for UCA. Analytical BER upper bounds were shown to closely match the simulation results at moderate-to-high SNRs. Numerical results showed that GSM can achieve better performance compared to SMP and SM in ULA and UCA. We then proposed a new signaling scheme called SAIM (subarray index modulation) which exploited spatial indexing across subarrays and multiple symbol transmissions within subarrays. Numerical results showed that the proposed SAIM scheme can outperform SMP, SM, and GSM schemes.

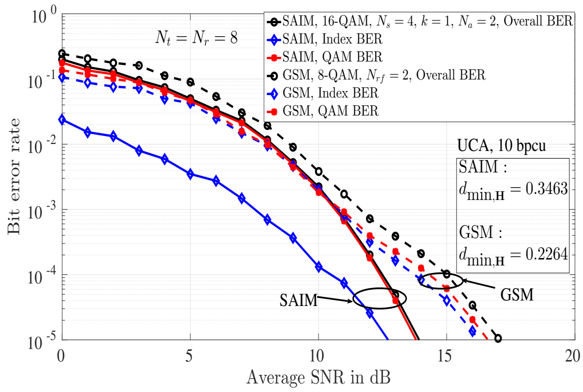

Fig. 10. Plot of index bits BER, QAM bits BER, and overall BER of GSM and SAIM in LOS MIMO systems with UCA operating at 60 GHz with $N_t = N_r = 8$, $D = 3$m, $r = 72.89$mm, 10 bpcu.

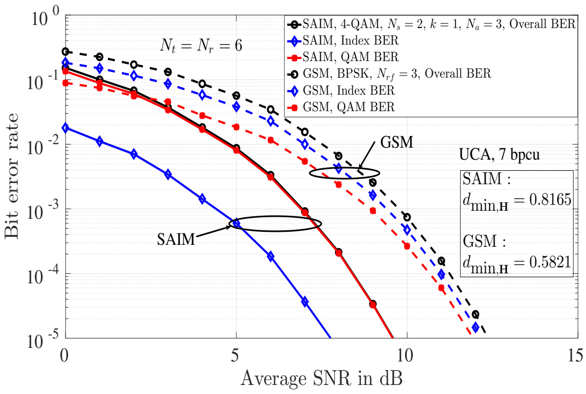

Fig. 11. Plot of index bits BER, QAM bits BER, and overall BER of GSM and SAIM in LOS MIMO systems with UCA operating at 60 GHz with $N_t = N_r = 6$, $D = 3$m, $r = 68.59$mm, 7 bpcu.

REFERENCES

[1] T. S. Rappaport, R. W. Heath, Jr., J. N. Murdock, and R. C. Daniels, *Millimeter Wave Wireless Communications*, Prentice Hall, 2014.

[2] I. Sarris and A. R. Nix, "Design and performance assessment of high-capacity MIMO architectures in the presence of a line-of-sight component," *IEEE Trans. Veh. Tech.*, vol. 56, no. 4, pp. 2194-2202, Jul. 2007.

[3] F. Bohagen, P. Orten, and G. Oien, "Design of optimal high-rank line-of-sight MIMO channels," *IEEE Trans. Wireless Commun.*, vol. 6, no. 4, pp. 1420-1425, Apr. 2007.

[4] L. Zhou and Y. Ohashi, "Low complexity millimeter-wave LOS-MIMO precoding systems for uniform circular arrays," *Proc. IEEE WCNC'2014*, pp. 1293-1297, Apr. 2014.

[5] P. Wang, Y. Li, and B. Vucetic, "Millimeter wave communications with symmetric uniform circular antenna arrays," *IEEE Commun. Lett.*, vol. 18, no. 8, pp. 1307-1310, Aug. 2014.

[6] S. Sun, T. Rappaport, R. W. Heath, Jr., A. Nix, and S. Rangan, "MIMO for millimeter wave wireless communications: beamforming, spatial multiplexing, or both?," *IEEE Commun. Mag.*, vol. 52, no. 12, pp. 110-121, Dec. 2014.

[7] Y. Jeon, M. Kim, G-T. Gil, and Y. H. Lee, "LoS spatial multiplexing and beamforming using uniform circular array of subarrays," *Proc. IEEE VTC-Spring'2016*, pp. 1-5, May 2016.

[8] M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial modulation for generalized MIMO: Challenges, opportunities, implementation," *Proc. IEEE*, vol. 102, no. 1, pp. 56-103, Jan. 2014.

[9] A. Chockalingam and B. Sundar Rajan, *Large MIMO systems*, Cambridge Univ. Press, 2014.

[10] P. Liu and A. Springer. "Space shift keying for LOS communication at mmWave frequencies," *IEEE Wireless Commun. Lett.*, vol. 4, no. 2, pp. 121-124, Apr. 2015.

[11] P. Liu, M. Di Renzo, and A. Springer, "Line-of-sight (LOS) spatial modulation (SM) for indoor mmWave communication at 60 GHz," *IEEE Trans. Wireless Commun.*, 2016. DOI: 10.1109/TWC.2016.2601616.

[12] N. Ishikawa, R. Rajashekar, S. Sugiura, and Lajos Hanzo, "Generalized spatial modulation based reduced-RF-Chain millimeter-wave communications," *IEEE Trans. Veh. Tech.*, 2016. DOI: 10.1109/TVT.2016.2555378.

[13] L. Liu et al. "Characterization of line-of-sight MIMO channel for fixed wireless communications," *IEEE Ant. and Wireless Prop. Lett.*, vol. 6, pp. 36-39, 2007.