Multi-User Steered Multi-Set Space-Time Shift-Keying for Millimeter-Wave Communications

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***Abstract*—The recently proposed concept of Multi-Set Space-Time Shift Keying (MS-STSK) is intrinsically amalgamated with the Multiple-Input Multiple-Output (MIMO) philosophy for the sake of enhancing the attainable system throughput. Explicitly, we propose a Multi-User (MU) Steered MS-STSK (MU-SMS-STSK) scheme for the downlink of millimeter wave (mmWave) communications, which is combined with analogue beamforming relying on phase shifters and power amplifiers in order to overcome the high attenuation of mmWaves. Hence, our MU-SMS-STSK system combines the concepts of MU-MIMO, MS-STSK, beamforming and Orthogonal Frequency-Division Multiplexing (OFDM) for communicating with multiple users relying on the same time and frequency resources.**

***Index Terms*—MU-MIMO, Millimeter Waves, Multifunctional Antenna Array, MS-STSK, OFDM.**

I. Introduction

The millimeter-wave (mmWave) spectrum spanning between 30 GHz and 300 GHz has attracted substantial research interests over the past few years due to its large available bandwidth capable of fulfilling the increased capacity demand of future wireless systems [1]. However, mmWaves suffer from high attenuations compared to the benign sub-3 GHz band. To overcome the devastating attenuation effects, a mmWave wireless system should invoke beamforming, which is considered as a key enabling technology for operating at mmWaves [2].
Multi-functional (MF) multiple-input multiple-output (MIMO) techniques are capable of simultaneously achieving multiple MIMO benefits [3], hence potentially improving both the throughput and integrity in addition to the BF gain to overcome the high mmWave attenuations. For instance, the layered scheme of [4] combines the advantages of both space-time block codes (STBC) [5] and of the Vertical-Bell Laboratories Layered Space-Time (V-BLAST) scheme [6] combined with an additional BF gain. Space-time shift keying (STSK) [7] is one of the most effective MF-MIMO techniques, striking a compelling trade-off between the attainable multiplexing gain and diversity gain. In [8] we employed the STSK concept in the downlink (DL) of mmWaves in the new context of Layered Multi-Group Steered Space-Time Shift Keying (LMG-SSTSK), where for the sake of supporting multiple users, the antenna arrays available are divided into layers, each serving a distinct user group. Furthermore, the LMG-SSTSK system applied ABF in order to overcome the high path loss.

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Furthermore, a more recent MF-MIMO system referred to as the Multi-Set STSK (MS-STSK) was proposed in [9]. In the MS-STSK scheme, the idea of Spatial Modulation (SM) [10] - where a single antenna element is activated to transmit a single classic symbol, whilst conveying extra implicit information in the antenna index domain, whilst additionally providing a diversity gain [11] - is extended to transmit a coded block over a specific combination of antennas. The MS-STSK scheme requires a modest number of TAs and radio frequency (RF) chains,whilst achieving a higher throughput and improved integrity compared to the original STSK scheme.
The novel contributions of this paper are as follows:
(i) we propose a multi-user (MU) Steered MS-STSK (MU-SMS-STSK) system in the DL of mmWaves, where a single base station (BS) serves multiple users with the aid of MU transmit precoding (MU-TPC) at the BS. (ii) The proposed system is capable of achieving higher throughput than the LMG-SSTSK system of [8] *with the aid of employing the MS-STSK scheme of* [9] *rather than the STSK* of [7]. For MU-SM, the authors of [12] proposed a MU scheme, where the total number of antennas is divided into K groups of multiple antennas in order to serve K users in the DL. However here, we employ MU-TPC to serve multiple users that are angularly close enough to receive the same transmitted beam, while being far enough so that they experience independent fading. This is an important constraint in mmWaves, where angularly distinct users cannot receive the same mmWave signal due to the associated high attenuation. Furthermore, we employ orthogonal frequency-division multiplexing (OFDM) to overcome the effects of the dispersive mmWave channel [13].
The rest of the paper is organized as follows. In Section II, we present our proposed mmWaves MU-MS-STSK system concept. Then in Section III we provide our simulation results and finally we conclude in Section IV.

II. System Model

In this paper, we consider a multi-user downlink MIMO system, where a single BS serves K users mapped to the same time and frequency resources. The BS is equipped with N_{RF}^t RF chains, while each user is equipped with N_{RF}^r RF chains and each RF chain is connected to a single antenna array of N_{AA}^t and N_{AA}^r antenna elements at the transmitter and receiver, respectively. Each antenna element has a phase shifter and power amplifier for analogue beamforming. We assume that the total number of RAAs of all users sums up to $N_R = \sum_i^K N_{RF}^r(i) < N_{RF}^t$ to obey the condition required for linear MU-precoding (MU-TPC) [14].

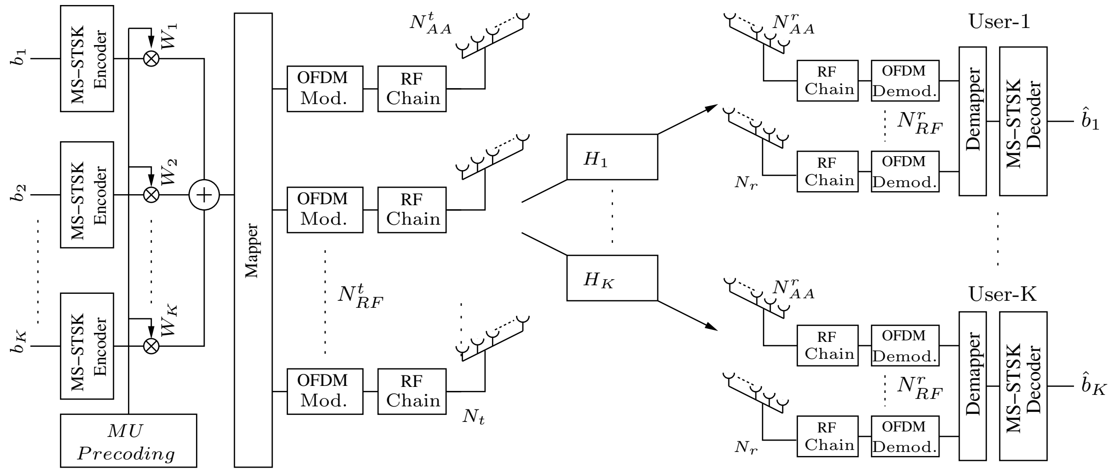

Figure 1. Block diagram of the MU-SMS-STSK system, where a single BS serves K users given that perfect CSI estimation of $\{H_k\}_{k=1}^{K}$ is assumed at the transmitter.

The block diagram of the system is shown in Figure 1, where the input bits of each user are encoded by a digital MS-STSK encoder [9] dedicated to generate the space-time codeword for each user. The MS-STSK scheme is a SM-MIMO technique, which transmits extra information using the index of the activated set of transmit antennas in addition to an STSK codeword. This technique is capable of achieving better integrity and higher throughput than the conventional STSK scheme [7]. The MS-STSK codeword is generated as follows: the bits fed into each MS-STSK encoder are divided into two parts, the first $B_1 = \log_2(M_c M_Q)$ bits are fed into the STSK encoder to generate an STSK codeword $X = A_q x_l \in \mathbb{C}^{M\times T}$ by spreading the input bits over M antennas and T time slots, where $\{A_q\}_{q=1}^{M_Q}$ denotes the activated dispersion matrix out of the entire set of M_Q matrices and x_l is the classic M_c-PSK/QAM symbol. The STSK encoder is referred to as the STSK(M, T, M_Q, M_cPSK/QAM) scheme.

The next $B_2 = \log_2(\mathcal{C})$ bits are used for selecting the activated Antenna Combination (AC), with $\mathcal{C}$ being the number of ACs available, which is known for both the BS and the users. In the MS-STSK scheme proposed in [9], a specific antenna combination denotes the activated set of antennas needed for the STSK codeword transmission, while the other antennas remain passive.

In MU-SMS-STSK, we use linear MU-TPC to simultaneously convey information to multiple users, where all users' codewords are superimposed prior to transmission, which means that the silent antennas in one user's codeword may be activated in another user's codeword. Hence, for the MU-SMS-STSK, all available antennas are activated, which implies that the AC in MS-STSK for a specific user becomes a Virtual AC (VAC), where the aim is to increase the attainable throughput. The number of VACs denoted by $\mathcal{C}$ is defined by the number of STSK codeword combinations over a specific number of Virtual Transmit Antennas (VTA) N_v and it is expressed as $\mathcal{C} = \left\lfloor \begin{pmatrix} N_v \\ M \end{pmatrix} \right\rfloor_{2^p}$, where the resultant value is rounded to the nearest base-2 integer and we have $p = \log_2(\mathcal{C})$. The number of VTAs is equal to the number RAAs of each user, yielding $N_v = N^r_{RF}$. The resultant final MS-STSK codeword can be expressed as

$$\bar{S} \quad = (X)_c \quad = \bar{A}_{q,c}\, x_l, \tag{1}$$

where $\bar{S} \in \mathbb{C}^{N_v \times T}$, $c = 1, \ldots, \mathcal{C}$. $\bar{A}_{q,c} \in \mathbb{C}^{N_v\times T}$ denotes the MS-STSK equivalent dispersion matrix and, which be expressed as $\tilde{A}_{q,c} = e^{j\theta_c} \cdot [\mathbf{0} \ldots A_{q,m} \ldots \mathbf{0}]^T$, given that $m = 1, \ldots, M$, $A_{q,m}$ denotes the $(1\times T)$-elements m-th row of A_q and θ_c is the phase-shift of the c-th VAC, which is known to both the transmitter and receiver, while $\mathbf{0}$ is a $(1 \times T)$-element vector of zeros [9]. The location of $A_{q,m}$ in $\tilde{A}_{q,c}$ is associated with the predefined VAC, where nonzero rows of $\tilde{A}_{q,c}$ indicate the active VTA for this specific user, while zero rows represent the silent VTAs of this specific user.

The MS-STSK encoder of the k-th user in Figure 1 generates N_{sc} MS-STSK codewords for transmitting simultaneously with other users' codewords over an OFDM symbol associated with N_{sc} sub-carriers with the aid of linear MU-TPC based on Block Diagonalization (BD) [15] following the philosophy of [8]. The n_{sc}-th precoded MS-STSK codeword of the k-th user is defined by $S_k(n_{sc}) = W_k(n_{sc})\bar{S}_k(n_{sc})$, where $n_{sc} = 1, 2, \ldots, N_{sc}$ and $W_k(n_{sc}) \in \mathbb{C}^{N^t_{RF}\times N_v}$ is the MU-TPC matrix applied to the k-th user's codeword $\bar{S}_k(n_{sc})$ transmitted over the n_{sc}-th sub-carrier. Next, all the K n_{sc}-th precoded MS-STSK codewords are superimposed using an adder to transmit the superimposed signal $S(n_{sc}) = \sum_{k=1}^{K} S_k(n_{sc})$.

Without loss of generality, we present an introduction example in order to further clarify the encoding process of the proposed MU scheme. Consider a BS having $N^t_{RF} = 8$ TAAs communicating with two users each equipped with $N^r_{RF} = 4$ RAAs. The BS utilizes a pair of distinct digital MS-STKS encoders serving each user, where each employs an STSK(2, 2, 4, 4QAM) encoder and $N^r_{RF} = 4$ RAAs. Given that we have $N_v = N^r_{RF}$ and $M = 2$, the (2×2)-element STSK codeword generated by each of the encoders can have $\mathcal{C} = \left\lfloor \begin{pmatrix} 4 \\ 2 \end{pmatrix} \right\rfloor_{2^p} = 4$ VACs, where the n_{sc}-th MS-STSK codeword destined to the k-th user can have one of the following combinations

$$\bar{S}_k(n_{sc}) = \begin{bmatrix} \bar{\mathbf{s}}_{k,1} \\ \bar{\mathbf{s}}_{k,2} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix}, \begin{bmatrix} \bar{\mathbf{s}}_{k,1} \\ \mathbf{0} \\ \bar{\mathbf{s}}_{k,2} \\ \mathbf{0} \end{bmatrix}, \begin{bmatrix} \bar{\mathbf{s}}_{k,1} \\ \mathbf{0} \\ \mathbf{0} \\ \bar{\mathbf{s}}_{k,2} \end{bmatrix} \quad (2)$$

$$or \begin{bmatrix} \mathbf{0} \\ \bar{\mathbf{s}}_{k,1} \\ \bar{\mathbf{s}}_{k,2} \\ \mathbf{0} \end{bmatrix}, \quad (3)$$

given that $\bar{\mathbf{s}}_{k,m} \in \mathbb{C}^{1\times T}$ is the m-th row of $\bar{S}_k(n_{sc})$ at the n_{sc}-th sub-carrier and $T = 2$ STSK time slots. Next, after applying the MU-TPC, the precoded n_{sc}-th MS-STSK codeword of the k-th user can be expressed as $S_k(n_{sc}) = [\ \mathbf{s}_{k,1}(n_{sc}) \quad \mathbf{s}_{k,2}(n_{sc}) \quad \dots \quad \mathbf{s}_{k,8}(n_{sc})\ ]^T$, where $\mathbf{s}_{k,n_t} \in \mathbb{C}^{1\times 2}$ denotes the m-th row of $S_k(n_{sc})$. Subsequently, the adder adds the two precoded n_{sc}-th MS-STSK codewords of user 1 and 2, yielding $S(n_{sc}) = S_1(n_{sc}) + S_2(n_{sc})$, where $S(n_{sc}) = [\ \mathbf{s}_1(n_{sc}) \quad \mathbf{s}_2(n_{sc}) \quad \dots \quad \mathbf{s}_8(n_{sc})\ ]^T \in \mathbb{C}^{8\times 2}$ is a matrix to be mapped to the n_{sc}-th sub-carrier, which has non-zero rows.

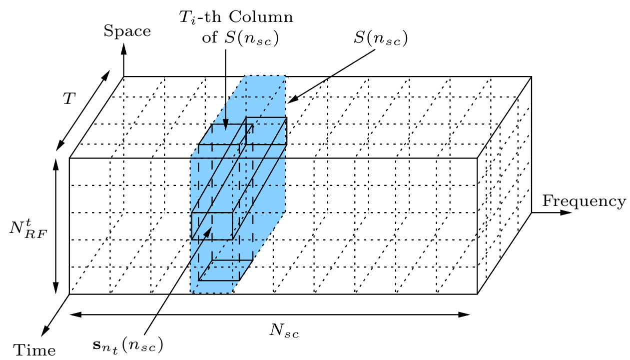

Figure 2. The transmitted MS-STSK OFDM symbols over T time slots. The blue section represents $S(n_{sc})$, which is the n_{sc}-th precoded MS-STSK codeword and $\mathbf{s}_{n_t}(n_{sc})$ denotes its n_t-th row transmitted by the n_t-th TAA. Furthermore, the T_i-th column of $S(n_{sc})$ is transmitted over the T_i-th OFDM symbol associated with $T_i = 1, \dots, T$.

Two main techniques exist in the literature for mapping multiple STSK codewords to OFDM symbols in [16] and [17]. In this contribution we follow the mapping technique of [17], where as shown in Figure 2 T OFDM symbols are transmitted over T time slots for the sake of transmitting all the n_{sc} precoded MS-STSK codewords. In Figure 2, the n_{sc}-th symbol $S(n_{sc}) = [\ \mathbf{s}_{n_t}(n_{sc}) \quad \mathbf{s}_{n_t}(n_{sc}) \quad \dots \quad \mathbf{s}_{n_t}(n_{sc})\ ]^T \in \mathbb{C}^{N^t_{RF}\times T}$ is transmitted over the n_{sc}-th sub-carrier, while its n_t-th row $\mathbf{s}_{n_t}(n_{sc})$ is transmitted by the n_t-th TAA. Furthermore, the T_i-th column of $S(n_{sc})$ is transmitted over the T_i-th OFDM symbol associated with $T_i = 1, \dots, T$.

Owing to the fact that the proposed MU-SMS-STSK system operates at mmWaves, again, ABF is employed relying on phase-shifters and power amplifiers connected to each antenna element of the antenna arrays for the sake of mitigating the effect of the high attenuations under the assumption of having a delay spread confined within the cyclic prefix (CP) of the OFDM symbol, the received signal of the k-th user over the n_{sc}-th sub-carrier is given by

$$\begin{aligned} Y_k(n_{sc}) = {} & P_k(n_{sc})H_k(n_{sc})F(n_{sc})S_k(n_{sc}) + \\ & \sum_{j\neq k}^{K} P_k(n_{sc})H_k(n_{sc})F(n_{sc})S_j(n_{sc}) + \\ & \hat{N}(n_{sc}), \end{aligned} \quad (4)$$

where $Y_k(n_{sc})$ is the received baseband $(N^r_{RF} \times T)$ signal after T STSK time slots, n_{sc} refers to the n_{sc}-th sub-carrier, $F(n_{sc}) \in \mathbb{C}^{N_t\times N^t_{RF}}$ and $P_k(n_{sc}) \in \mathbb{C}^{N^r_{RF}\times N_r}$ represent the diagonal analogue transmit and receive beamforming matrices applied at the BS and the k-th user, respectively. Furthermore, $H_k(n_{sc})$ denotes the $(N_r \times N_t)$ frequency domain mmWave channel between the BS and the k-th user at a specific sub-carrier, while the received interference denoted by $\sum_{j\neq k}^{K} P_k(n_{sc})H_k(n_{sc})F(n_{sc})S_j(n_{sc})$ represents the undesired information of other users at the k-th user and $\hat{N}(n_{sc}) \in \mathbb{C}^{N_r\times T}$ is the zero-mean additive White Gaussian noise (AWGN). The ABF diagonal matrix of the transmitted can be expressed as

$$F(n_{sc}) = diag\left\{\mathbf{f}(\varphi^{Tx}_1), \dots, \mathbf{f}(\varphi^{Tx}_{n_t}), \dots, \mathbf{f}(\varphi^{Tx}_{N^t_c})\right\}, \quad (5)$$

where $\mathbf{f}(\varphi^{Tx}_{n_t}) = [f(\varphi^{Tx}_{n_t,1}) \dots f(\varphi^{Tx}_{n_t,N^t_{AA}})]^T \in \mathbb{C}^{N^t_{AA}\times 1}$ is the steering vector of the n_t-th TAA with an azimuth steering angle $\varphi^{Tx}_{n_t}$, while the receive ABF can be expressed as

$$P_k(n_{sc}) = diag\left\{\mathbf{p}(\varphi^{Rx}_1), \dots, \mathbf{p}(\varphi^{Rx}_{n_r}), \dots, \mathbf{p}(\varphi^{Rx}_{N^r_c})\right\}, \quad (6)$$

where $\mathbf{p}(\varphi^{Rx}_{n_r}) = [p(\varphi^{Rx}_{n_r,1}) \dots p(\varphi^{Rx}_{n_r,N^r_{AA}})]^T \in \mathbb{C}^{N^r_{AA}\times 1}$ is the steering vector of the n_r-th RAA with an azimuth receive steering vector $\varphi^{Rx}_{n_r}$. Assuming a Uniform Linear Array (ULA) geometry at each TAA, the steering vector of the n_t-th TAA defined by $\mathbf{f}(\varphi^{Tx}_{n_t})$ in (5) can be expressed as

$$\mathbf{f}(\theta^{Tx}_{n_t}) = \frac{1}{\sqrt{N^{AA}_t}}\left[1, \dots, e^{j2\pi m.d_t \sin(\varphi^{Tx}_{n_t})}, \dots\right], \quad (7)$$

where $m = 0, \dots, N^{AA}_t - 1$ corresponds to the antenna element's index in the n_t-th array and d_t denotes the element-separation distance in terms of the wavelength λ with the constraint of $d_t \leq \frac{\lambda}{2}$ in order to achieve a beneficial beamforming gain. Similarly, under the same assumption of a ULA geometry at each RAA, the steering vector of the n_r-th RAA defined by $\mathbf{p}(\varphi^{Tx}_{n_t})$ in (6) is similar to (7).

Again, due to the high attenuation, all users are considered to be angularly close enough[1] to receive the same transmitted signal [8], while they are sufficiently separated to experience independent fading. Thereby, signals transmitted with a given angle of departure (AoD) would be received by the users with an approximately similar angle of arrival (AoA) [18]. A technique similar to that of [8] can also be applied in order to communicate with users having different pairs of AoD and AoA. Hence, the transmitter simultaneously applies the ABF matrix at each sub-carrier $F(n_{sc})$ in the direction of all users, while the ABF applied at the j-th user terminal $P_k(n_{sc})$ is slightly different from the ABF applied at the k-th user terminal.

[1]Angularly close users in mmWaves form a group users receiving the same transmitted signal beam, since in mmWaves the transmitter cannot reach angularly distinctive users simultaneously [8].

Now, the effective channel between the BS and the k-th user, which denotes the post-beamforming channel matrix $\bar{H}_k(n_{sc}) \in \mathbb{C}^{N^r_{RF} \times N^t_{RF}}$ can be expressed as

$$\bar{H}_k(n_{sc}) = P_k(n_{sc}) H_k(n_{sc}) F(n_{sc}). \quad (8)$$

By employing the BD for MU-TPC [15], the effective channels of each user are assumed to be known at the transmitter, which uses $\left[\bar{H}_1(n_{sc}) \ldots \bar{H}_K(n_{sc})\right]$ in order to construct the MU-TPC matrix $W_k(n_{sc})$ of the k-th user. Therefore, the linear MU-TPC technique employed ensures that the interference imposed by the other users at the k-th user is canceled, yielding $\bar{H}_k(n_{sc}) W_j(n_{sc}) = \begin{cases} Z_k(n_{sc}) & , j = k \\ 0 & , j \neq k \end{cases}$.
Hence, the signal received at the k-th user is expressed as

$$\begin{aligned} Y_k(n_{sc}) &= \bar{H}_k(n_{sc}) S_k(n_{sc}) + \\ & \underbrace{\sum_{j \neq k}^{K} \bar{H}_k(n_{sc}) S_j(n_{sc})}_{\approx 0} \\ & + \hat{N}(n_{sc}), \\ &= Z_K(n_{sc}) \bar{S}_k(n_{sc}) + \hat{N}(n_{sc}). \end{aligned} \quad (9)$$

Now, with the aid of a Maximum Likelihood (ML) detector, and under the assumption of having the knowledge of $Z_k(n_{sc})$ at the k-th user, the estimates of the dispersion matrix index, of the symbol index and of the VAC index referred to here as $\hat{q}$, $\hat{l}$ and $\hat{c}$ at the n_{sc}-th sub-carrier can be detected according to

$$< \hat{q}, \hat{l}, \hat{c} >= \arg\min_{q,l,c} \left\| Y_k(n_{sc}) - Z_K(n_{sc}) \left(\bar{A}_{q,c} x_l \right) \right\|^2 .$$

The achievable throughput of the system is reduced, when adding the CP [17], which is relatively high at mmWaves. However, due to the huge bandwidth available, a high number of sub-carriers can be employed [8]. The achievable throughput per user can expressed as

$$R_k = \frac{\log_2(\mathcal{C} M_q M_c)}{\left(1 + \frac{N_{cp}}{N_{sc}}\right)} \, (bit/symbol), \quad (10)$$

which tends to $[R_k]_{\frac{N_{cp}}{N_{sc}} \approx 0} \rightarrow \log_2(\mathcal{C} M_q M_c) \, (bit/symbol)$ at a high number of sub-carriers.

III. Results

In this section we provide our Monte-Carlo simulation results characterizing the MU-SMS-STSK system, where we consider a DL senario having a single BS equipped with $N^t_{RF} = 16$ TAAs each having N^t_{AA} AEs serving K user terminals located at a maximum distance of 200 m in the DL. Each user is equipped with $N^r_{RF} = 4$ RAAs having N^r_{AA} AEs. The system operates over the 28 GHz mmWave band with the aid of $N_{sc} = 2048$ OFDM sub-carriers and CP=100. Each MS-STSK encoder of the BS has a total of $N_v = 4$ VTAs, which leads to a total of $\mathcal{C} = 4$ VACs with the aid of an embedded STSK(2, 2, 4, 4) encoder. The mmWave channel employed is the 28 GHz measurement-based statistical channel model proposed in [13]. *Based on Equation (*10*), the achievable throughput of the MU-SMS-STSK system over mmWaves using the specified configurations is equal to* $\frac{\log_2(4\times4\times4)}{\left(1+\frac{100}{2048}\right)} = 5.7207$ *bits/symbol per user.*

The BER performance of the aforementioned MU-SMS-STSK system supporting $K = 2$, 3 and 4 users is shown in Figure 3. The system is compared to a MU-STSK system, based on a single group assisted LMG-SSTSK arrangement [8] with an STSK(4 ,2, 4, 16) encoder, which achieves the same throughput. The curve characterizing the performance of the MU-SMS-STSK system without OFDM is represented by the ($\times$) marker. The figure shows that employing OFDM is essential at mmWaves, since the dispersive mmWave channel imposes an error floor. Furthermore, Figure 3 shows that with (N^t_{AA}, N^r_{AA})=(1, 1), the MU-SMS-STSK system outperforms the MU-STSK system by about 3, 2.5 and 0 dBs at a BER of 10^{-5}. Hence, when the maximum number of users supported by the MU-SMS-STSK scheme is reached, the same performance is achieved by both systems.

The enhanced performance of the MS-SMS-STSK system is achieved at the same complexity order as that of MU-STSK. Given the simulated systems configuration, the complexity order imposed is $\mathcal{O}(M_Q M_c \mathcal{C}) = \mathcal{O}(4 \times 4 \times 4) = \mathcal{O}(64)$ for MS-SMS-STSK and it is $\mathcal{O}(M_Q M_c) = \mathcal{O}(4 \times 16) = \mathcal{O}(64)$ for MU-STSK. The complexity order can be further reduced by employing the hard-limiter-based optimal detector of [9].

Moreover, when the antenna array configurations changes to (N^t_{AA}, N^r_{AA})=(2, 2) and (4, 2) for K =3, Figure 3 exhibits a substantial SNR gain of 6 dB and 9 dB, respectively.

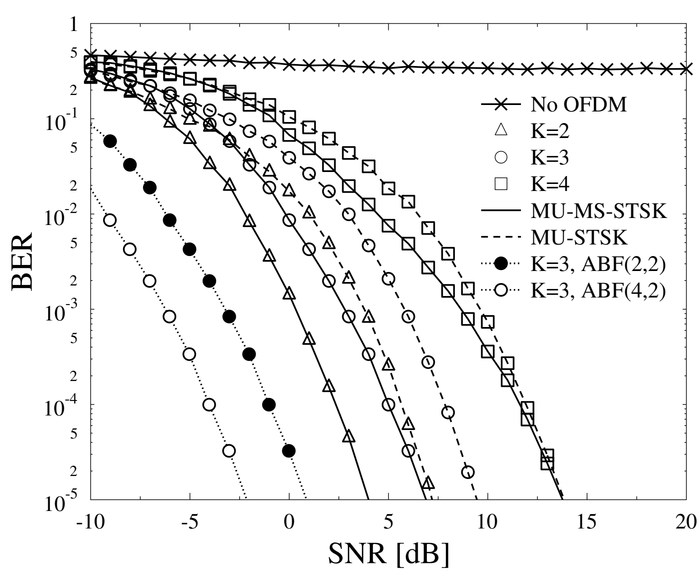

Figure 3. BER performance of uncoded MU-SMS-STSK system with a BS equipped with single AE $N^t_{RF} = 16$ TAAs, STSK(2, 2, 4, 4) digital encoder for each user, $N_v = 4$ VTAs and $\mathcal{C} = 4$ VACs serving K =2, 3 and 4 users over $N_{sc} = 2048$ OFDM sub-carriers over the 28 GHz mmWave channel. Each user is equipped with a single AE $N^r_{RF} = 4$ RAAs. Furthermore, to observe the effect of optimal ABF, the figure shows the performance of the system serving K= 2 users with ABF(N^t_{AA}, N^r_{AA}) = ABF(2, 2) and ABF(4, 2), which is capable of achieving an SNR gain of 6 dB and 9 dB, respectively. The performance of the the system without OFDM is shown in ($\times$).

IV. Conclusions

In this paper, we proposed a multi-user SMS-STSK system for the downlink of mmWave wireless systems. This MU system is capable of simultaneously serving multiple users over the same time-and frequency-resource at mmWaves and it is capable achieving a better performance than its MU-STSK counterpart. Furthermore, ABF is employed with the aid of phase-shifters and power amplifiers to overcome the high attenuation losses encountered at mmWaves. This system can be extended to a Multi-Group (MG) system as proposed in [8], where the TAAs can be divided into multiple layers to simultaneously serve multiple groups of users.

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