Integrating Spatial Modulation Into 802.11n

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***Abstract*—Spatial modulation (SM) is a newly emerging multiple-input multiple-output (MIMO) technique which actives only one transmit antenna at any time instant and provides improved energy efficiency and error performance as compared with convention MIMO techniques. In this paper, we propose to integrate SM into the IEEE 802.11n standard in order to improve the bit error rate (BER) performance when the transmitter and the receiver are both equipped with multiple antennas. Space-time block coding (STBC) defined in IEEE 802.11n standard is chosen as the representative of IEEE 802.11n MIMO techniques. Monte Carlo simulations are conducted to compare the performance of SM and STBC under various channels of Rayleigh multipath channel and the IEEE 802.11n B, D, E channel models. The simulation results show that SM can offer improved BER performance for most of the scenarios under various system setups.**

I. INTRODUCTION

MIMO has attracted increasing attention over the recent years. With multiple antennas deployed at both the transmitter and receiver, the communication system can achieve efficient trade-off between diversity, multiplexing and beam-forming gains without the need of any extra resources [1]. Various MIMO techniques, such as the vertical-Bell Laboratories layered space-time (V-BLAST) [2], and STBC [3] [4], have been proposed to exploit the potentials. OFDM is also a promising wireless communication technique which provides high spectrum efficiency and robustness against frequency selectivity. The combination of OFDM with MIMO, termed MIMO-OFDM, has already been included in many communication standards including the IEEE 802.11n wireless local area networks (WLAN) [5].

However, traditional MIMO schemes have several problems. On the one hand, V-BLAST suffers from sever inter-channel interference (ICI) at the receiver. Therefore, the detection algorithm at the receiver is usually very complex. On the other hand, although STBC is able to overcome the limitation of V-BLAST, it is at the price of reduced spectrum efficiency.

SM, as a novel MIMO technique [6]-[9], is believed to be a competitive approach to overcome the aforementioned problems. By activating only one antenna at any time instant and taking the active antenna index as additional resource of information carrier, SM has improved spectrum efficiency with the single stream transmission architecture. The single stream architecture also avoids ICI and enables low complexity detection algorithms at the receiver.

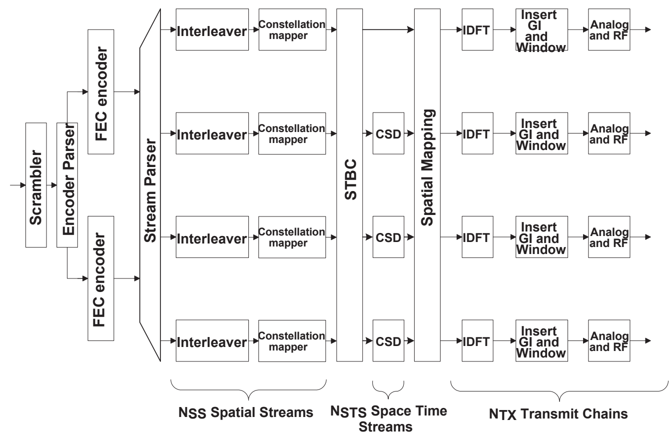

Fig. 1. Block diagram of IEEE 802.11n transmitter[5, p. 262].

Inspired by this, the aim of this paper is to investigate the feasibility of integrating SM into IEEE 802.11n in order to further improve the performance of original 802.11n MIMO techniques. To be more specific, we analyze the BER performance and find that SM can operate at lower signal-to-noise (SNR) ratio than the STBC schemes of current 802.11n standard to achieve a target BER for various system setups and propagation environments, and therefore, can improve the system reliability and coverage.

The rest of this paper is organized as follows. Section II reviews the MIMO techniques employed in IEEE 802.11n physical layer (PHY). Section III describes the system model of SM. Section IV presents the simulation results and discussion. And finally, Section V concludes the whole paper.

Notation: Lowercase bold letters denote vectors and uppercase bold letters denote matrices. $\lfloor \cdot \rfloor$ represents the floor operation. $\Re\{\cdot\}$ and $(\cdot)^*$ return the real part and the conjugate respectively. $(\cdot)^H$ denotes the Hermitian transpose operation. $\mathcal{CN}(0, \sigma^2)$ represents the distribution of a circularly symmetric complex Gaussian random value with variance σ^2.

II. IEEE 802.11N PHYSICAL LAYER

The block diagram of the IEEE 802.11n transmitter is shown in Fig.1. After the scrambler that reduces the probability of long sequences of zeros or ones, the incoming bits go through the encoder parser and the forward error correction (FEC) encoder to obtain the bits to be transmitted. Then, the stream parser divides the output bits into different spatial streams (SSs), which is defined as "One of several streams of bits or modulation symbols that may be transmitted over multiple spatial dimensions that are created by the use of multiple antennas at both ends of a communications link". the number of SS is defined as N_{SS}. Next, the bits of each SS is send to the interleaver to prevent long sequences of adjacent noisy bits from entering the BCC decoder. After the constellation mapper, the obtained symbol is send to the optional STBC encoder to obtain the space-time streams (STSs) that is defined to be "the streams of modulation symbols created by applying a combination of spatial and temporal processing to one or more spatial streams of modulation symbols", which is corresponding to the transmit antenna numbers and is represented by N_{TS}. After that, in order to prevent the unwanted beamforming effect, cyclic shift diversity is applied to decorrelate the STSs. Then, the spatial mapper pams the STSs to the transmit antenna chains according to direct mapping, spatial expansion or beamforming rules. After inverse discrete Fourier transform (IDFT), the obtained time domain signals at each transmit chain is appended with guard interval and windowed. Finally, the signal is converted to analog signals for RF transmission.

As can be seen from the transmitter structure, the main feature of the IEEE 802.11n PHY is that due to the implementation of MIMO, the 802.11n supports more than one SS and STS, i.e. it support multiple antenna to transmit multiple data streams. Thanks to this feature, the IEEE 802.11n allows the PHY data rate of up to 260Mbps and 540 Mbps over 20 MHz and 40 Mhz bandwidth, respectively. IEEE 802.11n supports MIMO techniques of spatial division multiplexing (SDM), receiver diversity (RxD) and STBC, where RxD can be applied together with SDM or STBC. As mentioned before, SDM (V-BLAST) offers maximum data rate, but it suffers from ICI and requires complex detector at the receiver, which results in higher SNR requirement at the receiver. As we know, the design of hardware to provide high SNR is not cost efficient, more effective methods are required to improve the robustness of 802.11n MIMO-OFDM systems in order to reduce the SNR requirement. Since STBC usually can offer better error performance and has more flexible transmitter side designs, i.e. flexible SS configurations, and therefore has more relaxed restrictions of the receive antenna numbers, in this paper, we choose STBC as the representative of IEEE 802.11n MIMO techniques to make comparison with the proposed SM schemes.

STBC is a promising solution to provide robust error performance due to its delicate design of the transmit symbol blocks that is able to provide transmit diversity. The supported STBC schemes in 802.11n amendment can be summarized as follows [10]: (1) $N_{SS}=1$ and $N_{TS}=2$; (2) $N_{SS}=2$ and $N_{TS}=3$; (3) $N_{SS}=2$ and $N_{TS}=4$; and (4) $N_{SS}=3$ and $N_{TS}=4$, which will be investigated to represent the performance of IEEE 802.11n. All the listed space time blocks are consisted of 2 symbols transmitted from the transmitter. Taking $N_{SS}=2$ and $N_{TS}=3$ as an example, at each subcarrier frequency, the modulated symbols transmitted at each transmit antenna are $[x_1,-x_2^*,x3]$ at the first symbol time and $[x_2,x_1^*,x4]$ at the second symbol time. Suppose 2 antennas are equipped at the receiver, the received signal for the STBC system can be described in vector forms as [11]

$$\begin{bmatrix} y_1 \\ y_2^* \\ y_3 \\ y_4^* \end{bmatrix} = \begin{bmatrix} h_{11} & -h_{12} & h_{13} & 0 \\ h_{12}^* & h_{11}^* & 0 & h_{13}^* \\ h_{21} & -h_{22} & h_{23} & 0 \\ h_{22}^* & h_{21}^* & 0 & h_{23}^* \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2^* \\ x_3 \\ x_4^* \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2^* \\ z_3 \\ z_4^* \end{bmatrix} \quad (1)$$

where y_1 and y_2 represent the symbols received at the first receive antenna at the first and the second symbol time, and y_1 and y_2 represent the symbols received at the second receive antenna at the first and the second symbol time, respectively. the channel gain between the j-th transmit antenna and the i-th receive antenna is denoted by h_{ij}. $Z_i \sim \mathcal{CN}(0,N_0)$ is the corresponding additive white Gaussian noise (AWGN). If more receive antennas are equipped at the receiver, the corresponding channel gain matrix can be obtained by simply expanding the columns of the above channel matrix.

The SNR for the 802.11n system can be expressed as:

$$SNR = \frac{E_b}{N_0}\left(\frac{N_{data}+N_{pilot}}{N_{FFT}}\right)(N_{BPSCS}r), \quad (2)$$

with E_b denoting the energy per bit. N_{FFT} is the fast Fourier transform length, N_{data} and N_{pilot} are the number of date subcarriers and pilot subcarriers, N_{BPSCS} is the number of bits per subcarrier per stream, r denotes the code rate of the binary convolutional code (BCC).

In this paper, we consider zero-forcing (ZF) equalizer at the receiver:

$$\mathbf{W}_{ZF} = \left(\mathbf{H}^H\mathbf{H}\right)^{-1}\mathbf{H}^H, \quad (3)$$

where $\mathbf{H}$ is the channel matrix.

III. System Model of Spatial Modualtion

Consider a MIMO system with an N_t antenna transmitter and an N_r antenna receiver. Since SM is carried out per subcarrier frequency independently, in the following, we drop the notation that specifies the subcarrier number to avoid cumbersome notation.

The modulation of SM at each subcarrier is processed as follows. Firstly, the SM mapper decide on a specific transmit antenna number according to $b_1=\lfloor log_2(N_t)\rfloor$ information bits, which will be referred to as space bits. Then, $b_2=log_2(M)$ constellation bits are mapped to the M-phase shift keying/quadrature amplitude modulation (PSK/QAM) constellation to obtain the symbol to be transmitted at the decided transmit antenna. The other transmit antenna is zero-padded. As can be seen from the process, in order to make full use of the transmit antennas, in SM, it would be better to set the transmit antenna number to be integer power of 2. The number of bits that can be transmitted on each subcarrier is

$$R_{SM} = \lfloor \log_2 (N_t) \rfloor + \log_2 (M). \quad (4)$$

To illustrate this, taking $N_t = 2$ and $M = 4$ as an example, Table I shows the corresponding SM mapping table. If '0' is the first information bit, the first antenna is chosen to be active, while an '1' is corresponding to activate the second transmit antenna. Then, the last 2 bits can be modulated to the 4PSK constellation to generate the symbol. Consequently, a total of 3 bits can be transmitted on each subcarrier for this system setup.

TABLE I
SM MAPPING TABLE FOR $N_t = 2, M = 4$

Input bits	$N_t = 2, M = 4$	
	Antenna number	Transmit symbol
000	1	1+j
001	1	-1+j
010	1	-1-j
011	1	1-j
100	2	1+j
101	2	-1+j
110	2	-1-j
111	2	1+j

After SM mapping ,the symbol to be transmitted at a certain subcarrier can be represented by

$$\mathbf{x} = s\mathbf{e}_j, \quad (5)$$

where $s \in \mathcal{S}$ is the modulated constellation symbol and $\mathcal{S}$ is the corresponding constellation. $\mathbf{e}_j \in \mathbb{C}^{N_t \times 1}$ is the j-th column drawn from the diagonal matrix I_{N_t}. The i-th element in $\mathbf{x}$ represents the symbol to be transmitted from the i-th transmit antenna. The corresponding received signal at the receiver therefore can be written as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \quad (6)$$

where $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix with its ij-th entry denoting the complex channel gain between the j-th transmit antenna and the i-th receive antenna. $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$ is the AWGN noise with its entries are i.i.d. Gaussian variables following $\mathcal{CN}(0, N_0)$.

The optimal maximum likelihood (ML) detection for SM is given by:

$$\underset{\forall \widehat{s} \in \mathcal{S}, \widehat{j} \in \{1,\ldots,N_t\}}{\arg\min} \left\| y - \mathbf{H}\widehat{s}\mathbf{e}_{\widehat{j}} \right\|^2 \quad (7)$$

IV. SIMULATION RESULTS AND DISCUSSION

In this section, Monte Carlo simulations are conducted to compare the performance of SM and STBC, and evaluate the feasibility of integrating SM into IEEE 802.11n. We assume the system to have 64 subcarriers operating within the bandwidth of 20MHz at the carrier frequency of 2.4GHz.

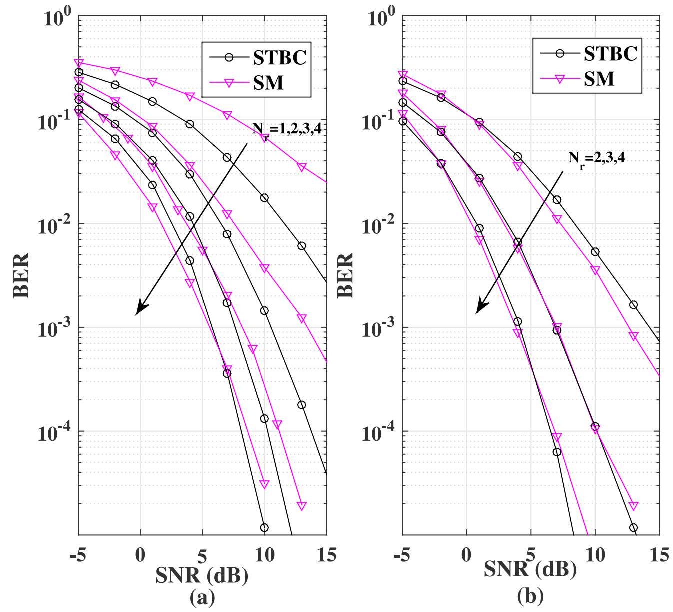

Fig. 2. Simulation results for the BER performance of SM and STBC under Rayleigh multi-path channel model with the system setups of: (a) $N_t = 2$, SM using 8PSK and STBC using MCS3; (b) $N_t = 4$, SM using QPSK and STBC using MCS9.

To simplify the simulation, we investigate the raw BER performance under the assumption of perfect channel state information a the receiver.

A wide range of channel models are considered in the simulation, including the multipath frequency selective Rayleigh channel and the 802.11n propagation channels. Specifically, we consider the IEEE 802.11n channel model B, D and E, which characterizes the indoor channel of the intra-room residential environment, typical office room and large office, respectively. Uniform linear antenna (ULA) arrays with antenna separation of full-wavelength (λ) at the transmitter and half-wave-length ($\lambda/2$) at the receiver are assumed for all channels. Also, the distance between the transmitter and the receiver is set to be 5m for channel model B, D and E, and the energy per bit E_b defined in (2) is set to be the received energy per bit at each receive antenna.

Since the IEEE 802.11n supports up to 4 transmit and receive antennas, in consideration of the fact that the transmit antenna number in SM is usually set to be integer power of 2, the systems with 2 antenna and 4 antenna transmitters are considered in the simulation with various receive antenna numbers. For the fairness of comparison, we set the SM and STBC systems to have the same spectrum efficiency. For 2 transmit antenna system, STBC uses the modulation and coding scheme (MCS) 3, which has one spatial stream and uses 16 QAM constellation, while SM uses 8PSK constellation to match the data rate. For 4 antenna system, STBC uses MCS9, i.e. 2 spatial streams and QPSK, and SM uses QPSK.

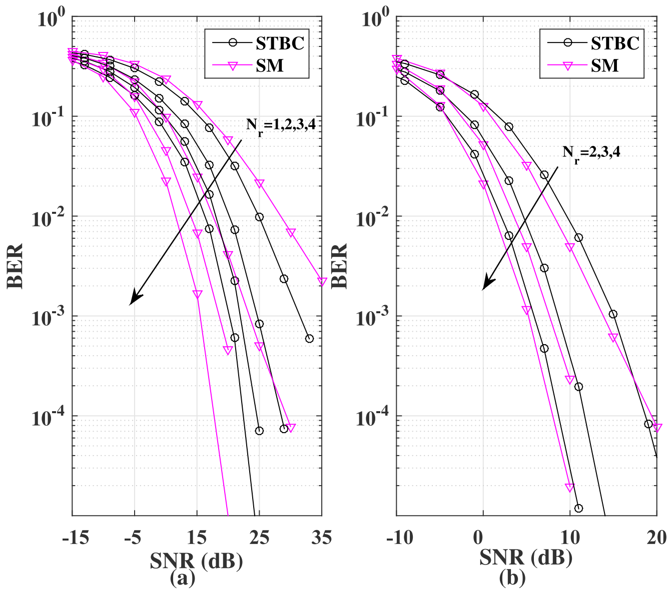

Fig. 3. Simulation results for the BER performance of SM and STBC under IEEE 802.11n B channel model with the system setups of: (a) $N_t = 2$, SM using 8PSK and STBC using MCS3; (b) $N_t = 4$, SM using QPSK and STBC using MCS9.

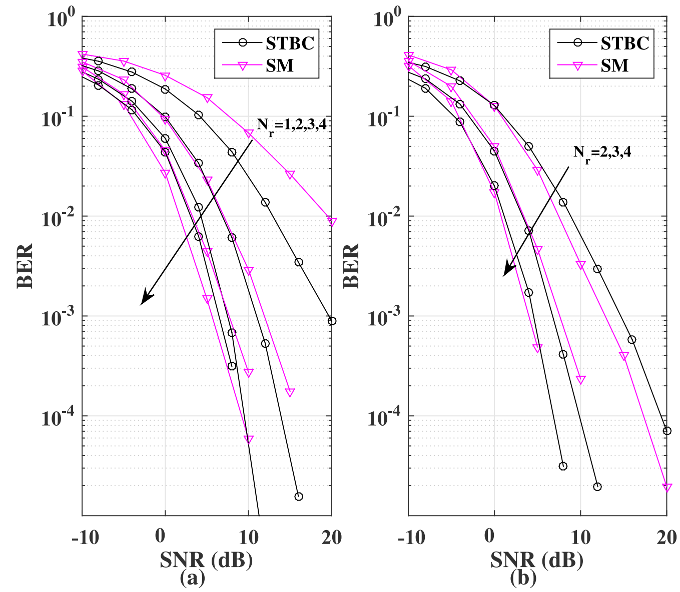

Fig. 4. Simulation results for the BER performance of SM and STBC under IEEE 802.11n D channel model with the system setups of: (a) $N_t = 2$, SM using 8PSK and STBC using MCS3; (b) $N_t = 4$, SM using QPSK and STBC using MCS9.

Fig. 2 shows the simulation results of SM and IEEE 802.11n STBC schemes in Rayleigh multipath channel that is consist of 6 channel taps. As can be seen from the left-hand side figure, when $N_t = 2$, and the receive antenna number is no larger than 2, SM has worse performance than STBC for all considered SNR region. However, as receive antenna number increases, the performance gap between SM and STBC narrows. For example, at a taget BER of 10^{-2}, STBC outperforms SM for more than 5 dB when $N_r = 1$. However, the gap shranks to about 1.5 dB when 2 antennas are equipped at the receiver. When the number of receive antenna further increases, SM demonstrates improved BER performance in low-to-medium SNR region. The performance gain at the BER of 10^{-2} is about 0.6 dB for $N_r = 3$ and is up to about 1 dB for $N_r = 4$. This can be explained by the fact that in low-to-medium SNR region, the error detection of SM mainly occurs in the constellation symbols instead of the transmit antenna indices. because of the lower modulation order, SM demonstrates improved performance as compared with STBC. However, it is also obvious from the figure that as the SNR becomes higher, STBC can offer better performance because of its higher transmit diversity order. When $N_t = 4$, as can be seen from the right-hand side figure, the result is very similar. SM slightly outperforms STBC at the BER of 10^{-2} for $N_r = 3, 4$. Surprisingly, when $N_r = 2$, an 1.5 dB performance improvement can be observed and it still holds when the SNR goes larger. Another phenomenon worth noting is that in low SNR region, SM always has degraded BER performance than STBC. This is due to the fact that when SNR is relatively low, error detection of the active transmit antenna number occurs more frequently for SM. When that happens, not only will the detector decode wrong space bits, the constellation bits will also be wrongly detected, which will result in severer error in the information bits.

Fig. 3 shows results for the IEEE 802.11n B channel model in order to evaluate the performance of SM and STBC in intra-room residential areas. The IEEE 802.11n B modle has the maximum delay τ_{max} of 80 ns and root mean square (rms) delay spread τ_{rms} of 15 ns. For the considered antenna spacing, the channel has ana envelope correlation of $\rho_{Tx} = 0.47$ for the transmitter side and $\rho_{Rx} = 0.88$ for the receiver side. As can be seen from the figure, the performance gain of SM is more obvious than that under Rayleigh channel. When $N_t = 2$, SM demonstrates about 2.5 dB SNR gain at the BER of 10^{-2} even when $N_r = 2$. And the gain is up to about 4.5 dB when $N_R = 3$ and 4. For $N_t = 4$, SM also demonstrates larger performance gain as compared with Rayleigh channel.

Fig. 4 and 5 show the simulation results for the IEEE 802.11n D channel model in order to evaluate the performance of SM and STBC in typical office rooms and large multi-story offices, respectively. The IEEE 802.11n D channel model has $\tau_{max} = 390ns$ and $\tau_{rms} = 50ns$, and for the considered antenna spacing, the channel has ana envelope correlation of $\rho_{Tx} = 0.47$ for the transmitter side and $\rho_{Rx} = 0.87$ for the receiver side. On the other hand, The IEEE 802.11n E channel model has $\tau_{max} = 730ns$ and $\tau_{rms} = 100ns$, and for the considered antenna spacing, the channel has ana

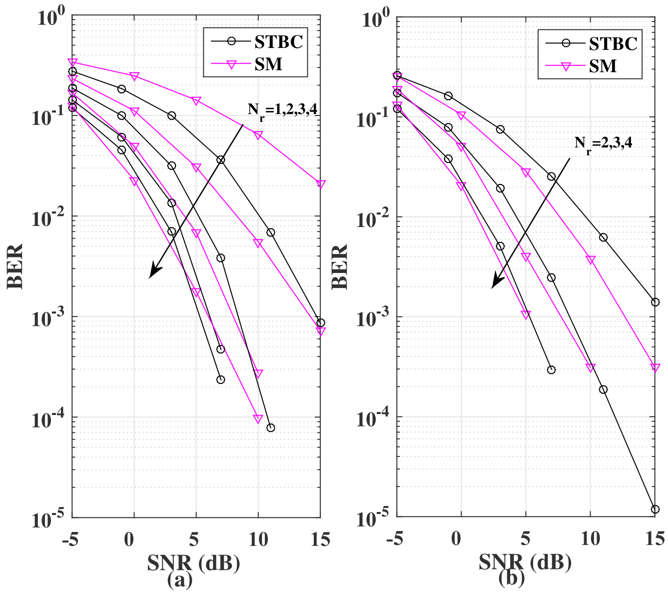

Fig. 5. Simulation results for the BER performance of SM and STBC under IEEE 802.11n E channel model with the system setups of: (a) $N_t = 2$, SM using 8PSK and STBC using MCS3; (b) $N_t = 4$, SM using QPSK and STBC using MCS9.

envelope correlation of $\rho_{Tx} = 0.47$ for the transmitter side and $\rho_{Rx} = 0.35$ for the receiver side. As can be seen from the figure, the result for channel model D is very similar to that in Rayleigh channel. However, for channel model E, SM exhibits worse performance than the above scenarios. For $N_t = 2$, the performance improvement only exists when $N_r = 4$. But luckily, SM still remains its advantage when $N_t = 4$ for arbitrary receive antenna numbers.

V. CONCLUSIONS

In this paper, we investigated the feasibility of implementing SM into IEEE 802.11n standard. In order to improve the PHY error performance, we propose to apply SM into the current IEEE 802.11n standard without changing the PHY designs. Monte Carlo simulations were conducted to evaluate the BER performance of SM and various STBC schemes applied in the IEEE 802.11n standard for both 2 transmit antenna and 4 transmit antenna scenarios under various realistic channel models defined in the IEEE 802.11n standard. The simulation results demonstrated that SM can offer better error performance in low-to-medium SNR region for all considered system setups especially when in residential channel models.

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