Adaptive Modulation With CAZAC Preamble-Based Signal-to-Noise-Ratio Estimator in OFDM Cooperative Communication System

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ABSTRACT
This paper presents an adaptive modulation in a single-input-single-output (SISO)-OFDM-based cooperative system that employs a Constant Amplitude Zero Autocorrelation (CAZAC) preamble-based SNR estimator. A novel CAZAC preamble-based SNR estimator that does not incur a throughput penalty is derived by exploiting a modified CAZAC preamble structure for the OFDM system. The proposed CAZAC SNR estimator is used to estimate the channel quality by finding the instantaneous SNR of the received cooperative data, which is sent to the transmitter via feedback channel. The modulation scheme is then changed according to the estimated SNR. The performance of the CAZAC preamble-based SNR estimator exhibits less than 0.02 dB and less than 0.2 dB bias when communicating over AWGN and SUI-5 channels, respectively. The proposed adaptive modulation scheme with the CAZAC SNR estimator significantly improved the channel throughput in comparison with the corresponding benchmark scheme dispensing with adaptive modulation that invokes $M$-PSK and $M$-QAM. More explicitly, the proposed adaptive modulation system with the CAZAC SNR estimator that invokes $M$-PSK exhibits significant improvement by about 5 dB at BER = $10^{-3}$ in comparison to its corresponding benchmark scheme dispensing with adaptive modulation when communicating over the SUI-5 channel. On the other hand, the relay-aided cooperative transmission exhibited an approximately 6 dB SNR gain in terms of channel throughput in comparison to the corresponding non-cooperative benchmark scheme, and benefited from spatial diversity.

INDEX TERMS
Adaptive modulation, spectral efficiency, OFDM, data-aided SNR estimator, constant amplitude zero autocorrelation preamble.

I. INTRODUCTION
The 5G mobile network is envisioned to support a wide range of diverse services, resulting in an increase in bandwidth demand. The potential applications range from high data rate applications, such as high speed video streaming, car-to-car or car-to-infrastructure communications, and general cellular communications, to low speed users, such as machine-to-machine communications and internet of things (IOT) applications [1]. Thus, the 5G network must be able
to accommodate a huge diversity in types of traffic. Some of the key issues that need to be considered are spectral efficiency, data throughput, power consumption, and transceiver complexity [2].

Therefore, in order to provide flexibility, scalability, and efficiency both in terms of power usage and spectrum, a new radio interface and radio access network have been developed, which is referred to as 5G New Radio (5G NR). Moreover, cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) was chosen for 5G NR [3]. OFDM provides good spectral efficiency and resilience to selective fading, which has made it an excellent waveform for 4G LTE.
Furthermore, it is also essential to consider employing a modulation scheme that provides a high level of spectral efficiency. There should be a balance between higher orders of modulation and noise performance. For the case of propagation environments that drastically fluctuate, using adaptive modulation and coding (AMC) techniques is one possible solution to this problem [4]. In this technique, the spectral efficiency is maximized by estimating the Signal-to-Noise-Ratio (SNR) at the receiver and feed the value back to the transmitter. The modulation and coding schemes are then changed according to the estimated SNR.

Another way of improving the efficiency of the wireless 5G networks can be achieved by deploying multiple antennas at the transmitter and the receiver, also known as multiple-input-multiple-output (MIMO) [5]. More specifically, the employment of multi-element array antennas in MIMO technology produces independent parallel channels in space. Hence, multiple data streams can be transmitted at the same time, which effectively increases the system’s transmission rate. However, it is a challenge to have multiple antennas in small devices due to their size and the required power consumption. A virtual MIMO scheme can be created when one mobile unit collaborates with one partner or a few partners jointly, which is referred to as cooperative communication [6], [7]. The two most popular collaborative protocols used between the source, relay and destination nodes are the Decode-And-Forward (DAF) as well as the Amplify-And-Forward (AAF) schemes. Hence, a virtual antenna array can be created by employing cooperative communication techniques, which does not require large power in a single unit.

A. RELATED WORKS

Adaptive modulation in cooperative communication have been studied, which resulted in enhanced channel capacity and spectrum efficiency, and minimized the BER of the system [8], [9], [10], [11]. More specifically, the studies in [8], [9], and [11] demonstrated that the employment of adaptive modulation in opportunistic relaying enhanced the spectral efficiency in cooperative relaying networks, by selecting the best relay node which provided the “best” end-to-end path between source and destination. Whilst, the authors in [10] studied the performance comparison of different channel estimators in AAF relaying. However, these studies considered SNR estimation in the frequency domain [8], [10], [11].

SNR estimators can be classified into two categories, namely, data-aided SNR (DA-SNR) estimators and non-data-aided SNR (NDA-SNR) estimators. The employment of SNR estimators imposes two main issues: computational complexity and feedback overhead. Key issues that need to be considered in designing SNR estimators are estimation accuracy, computational complexity, and data overhead. For the NDA-SNR estimator, SNR estimation is performed blindly without a priori information about the transmitted data [12], [13], [14], [15], [16].

For the DA-SNR estimator, SNR estimation is performed at the receiver using the training sequence or pilot data. Hence, it has higher estimation accuracy [17], [18], but at the expense of data overhead. The DA-SNR estimator has higher estimation accuracy than the NDA-SNR estimator but involves the insertion of a periodic pilot sequence, which is inefficient. Recently, there have been studies on preamble based DA-SNR estimators that can be classified into two groups: with and without throughput penalty [19], [20], [21]. The DA-SNR estimator that exploits the synchronization preamble does not incur a throughput penalty [20], [21]. The authors in [21] proposed a preamble-based SNR estimator that exploited synchronization preamble of [22], which is referred to as Schmidl preamble-based SNR estimator. The Schmidl preamble-based SNR estimator of [23], in particular, exploited time synchronization preamble for WiMAX IEEE 802.16d standard [24], [25].

Some of the methods used in the derivation of SNR estimations are maximum likelihood [19], second order moment criteria [20], second and fourth order moments (M2M4) [16], and autocorrelation function [17]. In [20], second-order moment criteria are used to derive the SNR expression. However, second-order moments involve probabilistic methods to derive an expression for SNR that has high complexity, as more multiplication and addition are required to estimate SNR in contrast to autocorrelation.

Explicitly, this paper extends the work in [26] by proposing Constant Amplitude Zero Autocorrelation (CAZAC) preamble-based SNR estimation that is invoked in an adaptive modulation of single-input-single-output (SISO)-OFDM-based cooperative system. The proposed system is referred to as the AM-CAZAC-OFDM cooperative system. The proposed CAZAC preamble-based SNR estimator is derived by exploiting the CAZAC synchronization preamble of [27]. The proposed CAZAC SNR estimator uses an autocorrelation function to estimate SNR. The performance of the proposed system is evaluated against the benchmark system that employs the Schmidl preamble-based SNR estimator of [23] and is referred to as the AM-Schmidl-OFDM cooperative system. The performance of the AM-CAZAC-OFDM cooperative scheme is also comparatively studied against the CAZAC-OFDM cooperative system with fixed modulation of $M$-PSK and $M$-QAM, which dispenses adaptive modulation.

B. CONTRIBUTIONS

The contributions of this work can be summarized as follows:

- A novel CAZAC preamble-based SNR estimator that does not incur a throughput penalty, is contrived. More specifically, the preamble-based SNR estimator using autocorrelation function is derived by utilizing an improved CAZAC time synchronization preamble of [27] that is designed for OFDM systems. The proposed CAZAC preamble-based SNR estimator exhibits a small bias when communicating over Additive White Gaussian Noise (AWGN) and Standard University Interim (SUI)-5 channels.
• An adaptive modulation in a SISO-OFDM-based cooperative system that invokes a CAZAC preamble-based SNR estimator is proposed in order to improve spectral efficiency. The studies consider the employment of two modulation formats, namely, $M$-PSK and $M$-QAM, for communication over AWGN and SUI-5 channels. The proposed AM-CAZAC-OFDM cooperative scheme significantly improved the channel throughput in comparison with the corresponding benchmark scheme dispensing with adaptive modulation.

• The relay-aided cooperative communication benefited from spatial diversity and resulted in significant improvement in terms of bit error rate (BER) and channel throughput in comparison to the corresponding non-cooperative benchmark scheme.

The remaining paper is constructed as follows. In Section II, the overall system model is presented. The derivation of CAZAC preamble-based SNR estimation and the switching threshold of adaptive modulation are presented in Section III. Performance analysis of the CAZAC preamble-based SNR estimator is presented in Section IV-A, whilst Section IV-B quantifies the performance of the preamble-based SNR estimator is used to estimate the channel quality by finding the instantaneous SNR of the received cooperative signal $Y_D$, which is sent to the transmitter via feedback channel as shown in Fig. 1. The modulation level is selected according to the instantaneous estimate of SNR and the criteria for selecting the SNR switching threshold is presented in Section III-C. In this work, two types of adaptive modulation schemes are studied, namely, $M$-PSK and $M$-QAM schemes.

## II. SYSTEM DESCRIPTION

In this paper, a SISO-OFDM-based single relay network where the source node, $S$, communicates with the destination node, $D$ with the assistance of the relay node, $R$, is considered. Fig. 1 shows the proposed AM-CAZAC-OFDM cooperative system. Each node employs a SISO-OFDM scheme as shown in Fig. 2, which also provides the definition of the OFDM modulator and demodulator blocks in Fig. 1. The source node, $S$, transmits OFDM signal to both the destination node, $D$, and relay node, $R$, and the received signals are denoted as $Y_{S\rightarrow D}$ and $Y_{S\rightarrow R}$, respectively. In this study, an OFDM system with $N$ subcarriers is assumed [28], and a conventional OFDM receiver is used at the relay and destination nodes. At the destination node, $D$, and the relay node, $R$, the received signal on the $k$th subcarrier can be written as [28]:

$$Y_{S\rightarrow D}(k) = \sqrt{E_S} H_{S\rightarrow D}(k) X(k) + N_D(k) \quad (1)$$

$$Y_{S\rightarrow R}(k) = \sqrt{E_S} H_{S\rightarrow R}(k) X(k) + N_R(k) \quad (2)$$

where $H_{S\rightarrow D}(k)$ is the $k$th subcarrier channel coefficient for $S \Rightarrow D$ link and $H_{S\rightarrow R}(k)$ is the $k$th subcarrier channel coefficient for the $S \Rightarrow R$ link. $N_D(k)$ and $N_R(k)$ are the $k$th subcarrier AWGN components observed at nodes $D$ and $R$, respectively. $E_S$ denotes average energy at node $S$ [29].

The received signal at the relay node, $Y_{S\rightarrow R}$, is OFDM demodulated, OFDM modulated and retransmitted to the destination node, $D$ as shown in Fig. 1. Subsequently, at the destination node, $D$, the signal on the $k$th subcarrier, $Y_{R\rightarrow D}(k)$ can be written as [29]:

$$Y_{R\rightarrow D}(k) = \sqrt{E_R} H_{R\rightarrow D}(k) Q(Y_{S\rightarrow R}(k)) + N(k) \quad (3)$$

where $E_R$ denotes average energy at node $R$ [29] and function $Q(.)$ denotes the decode and forward process of the $Y_{S\rightarrow R}$ signal. $N(k)$ is a zero mean Gaussian random variable with variance $N_0/2$ per dimension.

At the destination node, $D$, all the received $Y_{S\rightarrow D}$ and $Y_{R\rightarrow D}$ signals are combined using maximum ratio combining (MRC) method [30]. The MRC output signal for $j$ antennas, can be written as in Equation 4.

$$Y_D(k) = \sum_{i=1}^{j} H^*_{i\rightarrow D}(k) Y_{i\rightarrow D}(k) \quad (4)$$

where $H^*$ denotes the transpose conjugate of channel matrix between antenna at $i$th node and the destination node, $D$.

For a single relay case, $i$ denotes the antenna at nodes $S$ and $R$, and Equation 4 is simplified as:

$$Y_D(k) = H^*_{S\rightarrow D}(k) Y_{S\rightarrow D}(k) + H^*_{R\rightarrow D}(k) Y_{R\rightarrow D}(k) \quad (5)$$

where $H^*_{S\rightarrow D}$ is the transpose conjugate of channel matrix $H_{S\rightarrow D}$ for the $S \Rightarrow D$ link, whilst, $H^*_{R\rightarrow D}$ is the transpose conjugate of channel matrix $H_{R\rightarrow D}$ for the $R \Rightarrow D$ link. An SNR estimator is used to estimate the channel quality by finding the instantaneous SNR of the received cooperative signal $Y_D$, which is sent to the transmitter via feedback channel as shown in Fig. 1. The modulation level is selected according to the instantaneous estimate of SNR and the criteria for selecting the SNR switching threshold is presented in Section III-C.

### III. SNR ESTIMATION

In this contribution, the CAZAC time synchronization preamble of [27] is exploited for SNR estimation to estimate the channel quality for modulation level selection in the adaptive modulation scheme of the proposed AM-CAZAC-OFDM cooperative system. The CAZAC preamble structure is created with the length of one OFDM symbol. In order to improve time synchronization, the preamble is equally divided into four parts. The proposed CAZAC preamble structure used for the SNR estimation is shown in Fig. 3 where $C_z$ denotes the CAZAC sequence and $W$ represents the CAZAC weighted sequence with pseudo-noise (PN) sequence. The CAZAC weighted sequence, $W$, is obtained by multiplying the CAZAC sequence with a PN sequence of the same length using bitwise operation. The CAZAC and PN sequences are used because they have superior autocorrelation property and easy to generate. PN sequence has noise-like characteristic. Hence, the autocorrelation function of PN sequence is similar to Dirac delta function. The CAZAC sequence has advantageous properties of constant amplitude in the time domain and zero autocorrelation in the frequency and time domain.

### A. SNR ESTIMATION ALGORITHM

In [27] the CAZAC preamble structure is designed only for detection of the starting point of a frame, which is
meant for synchronization. In this work, the CAZAC preamble has been modified to follow the OFDM format, which has been utilized in the SNR estimation algorithm. The CAZAC preamble-based SNR estimation in the proposed AM-CAZAC-OFDM cooperative system is performed at the front end of the destination node, \( D \), receiver. The CAZAC preamble is loaded on the even subcarriers, while the odd subcarriers are loaded with zeros as per IEEE802.16d WiMAX OFDM standard format. The cyclic prefix, \( C_p \) of length \( N/4 \) where \( N = 256 \) bits, is used to avoid inter-symbol interference in the proposed AM-CAZAC-OFDM cooperative system as shown in Fig. 4. At the source node, \( S \), the autocorrelation of the transmitted signal is performed prior to the transmission over the wireless channel to the destination node, \( D \). At the destination node, \( D \) receiver, the autocorrelation of the MRC output signal \( Y_D \) is performed to estimate the instantaneous SNR, which is sent to the transmitter via feedback channel for the selection of the modulation level, as seen in Fig. 1.

At destination node, \( D \), the autocorrelation function of the MRC output signal, \( r_{dxx}(m) \), can be written as:

\[
r_{dxx}(m) = r_{ss}(m) + r_{ww}(m)
\]

where \( r_{ss}(m) \) and \( r_{ww}(m) \) denote the autocorrelation of the OFDM signal and the noise. In the case of transmission over an AWGN channel, the autocorrelation function of white noise is an impulse at zeroth lag where \( m = 0 \). Mathematically autocorrelation function of this modelled noise with magnitude given by the noise variance, \( \sigma^2 \), can be expressed as:

\[
r_{ww}(m) = \sigma^2 \delta(m)
\]

where \( \delta(m) \) represents a discrete delta sequence.
the MRC output signal, $Y_D$, as seen in Fig. 5. Hence, the estimated channel noise power added to the OFDM signal can be calculated by finding the difference between the estimated signal power and the peak value at zeroth lag, which can be expressed as:

$$\sigma_N^{2}_{est} = r_{dxx}(L_T) - (P_{ss})$$

where $r_{dxx}(L_T)$ represents zeroth-lag value. Therefore, the estimated SNR can be calculated using Equations 8 and 9 and the expression for the estimated SNR can be written as:

$$SNR_{est} = \frac{P_{ss}}{\sigma_N^{2}_{est}}$$

Hence, the performance index to measure the performance of SNR estimators is the normalized mean squared error (NMSE) which can be as expressed as:

$$NMSE = \frac{1}{M} \sum_{m=0}^{M-1} \frac{(SNR_{est} - SNR)^2}{SNR}$$

where $M$ is the number of instantaneous SNR values used, $SNR_{est}$ is the estimated SNR using Equation 10 and $SNR$ refers to the actual SNR.

### C. SWITCHING THRESHOLDS FOR ADAPTIVE MODULATION

The modulation level of $M$-PSK and $M$-QAM is selected according to the instantaneous estimate of SNR of the received cooperative signal $Y_D$. The threshold SNR to select the modulation level is derived using Fig. 6 and Fig. 7 such that it satisfies the predetermined BER of about $10^{-3}$ [31], [32]. More specifically, Fig. 6 and Fig. 7 show the performance of fixed modulation SISO-OFDM-based cooperative system of Fig. 2, when communicating over SUI-5 channel. The switching threshold SNR for $M$-PSK and $M$-QAM are presented in Table 1 and Table 2 respectively.

### IV. RESULTS AND DISCUSSION

This section presents the performance of the CAZAC preamble-based SNR estimator and the proposed AM-CAZAC-OFDM cooperative system of Fig. 1. More specifically, Section IV-A presents the performance of the CAZAC preamble-based SNR estimator for SISO-OFDM-based cooperative system of Fig. 1, dispensing with adaptive modulation that employs QPSK when communicating over AWGN and SUI-5 channels. The SISO-OFDM-based cooperative system that employs QPSK is referred to as

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**TABLE 1. Switching threshold SNR for $M$-PSK.**

| Mode | Modulation | Thresholds |
|------|------------|------------|
| 1    | QPSK       | SNR $\leq 11$ dB |
| 2    | 8PSK       | 11 dB $<$ SNR $\leq 16$ dB |
| 3    | 16PSK      | 16 dB $< $ SNR $\leq 21$ dB |
| 4    | 32PSK      | 21 dB $< $ SNR $\leq 26$ dB |
| 5    | 64PSK      | SNR $> 26$ dB |
the QPSK-OFDM cooperative system. Whilst Section IV-B presents the performance of the adaptive modulation for the AM-CAZAC-OFDM cooperative system of Fig. 1 that employs $M$-PSK and $M$-QAM when communicating over SUI-5 channels. The IFFT size, $N_{\text{ifft}} = 256$ bits and the length of guard band $C_p = 64$ bits are used in this work, in accordance with the IEEE802.16d standard [24], [25], [33]. The CAZAC time synchronization preamble with cyclic prefix of Fig. 4 is loaded on the even subcarriers with the frame length of $L_T = 320$ bits, as discussed in Section III. The parameters used in the simulations are outlined in Table 3 and in Table 4.

Moreover, this simulation considers communication over the SUI-5 channel, which is a member of SUI channel models adopted by IEEE802.16d standard [34]. This channel model consists of six channels that are grouped into three categories of outdoor terrain, namely, type A, type B, and type C as shown in Table 5 [34]. Terrain type A is hilly terrain with moderate-to-high tree densities. Terrain type C is flat terrain with light tree densities, while terrain type B is intermediate between terrain type A and terrain type C.

### Table 2. Switching threshold SNR for $M$-QAM.

| Mode | Modulation | Thresholds |
|------|------------|------------|
| 1    | 4QAM       | SNR $\leq 9$ dB |
| 2    | 8QAM       | 9 dB $< \text{SNR} \leq 14$ dB |
| 3    | 16QAM      | 14 dB $< \text{SNR} \leq 19$ dB |
| 4    | 32QAM      | 19 dB $< \text{SNR} \leq 24$ dB |
| 5    | 64QAM      | SNR $> 24$ dB |

### Table 3. OFDM system parameters [33].

| Parameters                        | Value               |
|-----------------------------------|---------------------|
| IFFT Size, $N_{\text{ifft}}$      | 256                 |
| Sampling Frequency, $F_s$         | 20 MHz              |
| Sub Carrier Spacing, $\Delta f = F_s/N_{\text{asied}}$ | $1 \times 10^5$ |
| Symbol Time, $T_s = 1/\Delta f$  | $1 \times 10^{-5}$ |
| Guard Interval Time, $T_g$        | $2.5 \times 10^{-6}$ |
| OFDM Symbol Time, $T_s = T_s + T_g$ | $1.25 \times 10^{-5}$ |
| Wireless channel used in simulations | AWGN, SUI-5        |

### Table 4. SUI-5 channel description [34].

| SUI-5 channel | Tap 1 | Tap 2 | Tap 3 | Unit |
|---------------|-------|-------|-------|------|
| Delay         | 0     | 4     | 10    | $\mu$ sec |
| Power         | 0     | -11   | -22   | dB   |
| $K_{factor}$  | 2     | 0     | 0     | -    |

### Table 5. Terrain type and corresponding SUI channels [34].

| Terrain Type | SUI Channels  |
|--------------|---------------|
| C            | SUI 1, SUI 2  |
| B            | SUI 5, SUI 4  |
| A            | SUI 5, SUI 6  |

A. PERFORMANCE OF SNR ESTIMATION

Performance of the CAZAC preamble-based SNR estimator is measured in terms of the estimated SNR, NMSE, and BER as a function of the actual SNR. Figures 8 and 10 depict comparisons between the estimated SNR and the actual SNR of the CAZAC preamble-based SNR estimator for QPSK-OFDM cooperative system and the QPSK-OFDM non-cooperative system of Fig. 2, when communicating over AWGN and SUI-5 channels, respectively. Based on the threshold SNR shown in Table 1, the QPSK modulation...
is chosen for performance analysis of channel SNR less than 11 dB. Similarly, the performance of the CAZAC preamble-based SNR estimator is also evaluated against that of the Schmidl preamble-based SNR estimator of [21].

For each actual SNR value, 2,000 iterations are performed to get the average value of the estimated SNR. Figures 9 and 11 are the closeup of Figures 8 and 10 for communication over AWGN and SUI-5 channels, respectively. In this work, the difference between the estimated SNR and the actual SNR is referred to as bias. It can be seen from Figures 9 and 11 that the estimated SNR exhibits smaller bias using the CAZAC preamble-based SNR estimator compared with that using the Schmidl preamble-based SNR estimator. The CAZAC preamble-based SNR estimator exhibits the smallest bias and has the smallest variance. In particular, in the QPSK-OFDM non-cooperative system, the CAZAC preamble-based SNR estimator exhibits less than 0.3 dB bias for the AWGN channel, as seen in Fig. 9. The CAZAC preamble-based SNR estimator performance is further improved in the QPSK-OFDM cooperative system, which exhibits less than 0.02 dB bias.

However, the performance of CAZAC SNR estimator degraded over the SUI-5 channel when it is compared to its performance over the AWGN channel. The CAZAC preamble-based SNR estimator exhibits almost 0.52 dB of bias in the QPSK-OFDM non-cooperative system, as seen in Fig. 11. Similarly, the performance of CAZAC SNR estimator is further improved in QPSK-OFDM cooperative system by exhibiting less than 0.2 dB bias.

The corresponding NMSE performance of the CAZAC SNR estimator for AWGN and SUI-5 channels, are shown in Fig. 12 and Fig. 13 respectively. The statistical NMSE reflects both the bias and the variance of an SNR estimate. It can be
observed in these figures that the QPSK-OFDM cooperative system with the CAZAC preamble-based SNR estimator outperforms the corresponding QPSK-OFDM cooperative system that invokes the Schmidl preamble-based SNR estimator for both AWGN and SUI-5 channels.

The BER performance of the QPSK-OFDM cooperative system when invoking CAZAC preamble as time synchronization preamble for AWGN and SUI-5 channels are shown in Fig. 14 and Fig. 15 respectively. It can be observed from Figure 15 that the employment of the CAZAC preamble in the QPSK-OFDM non-cooperative system (SISO) exhibits an approximately 0.5 dB SNR gain at BERs = 10^{-4}, in comparison to the QPSK-OFDM non-cooperative system that invokes Schmidl preamble as time synchronization preamble. It can also be seen from Fig. 15 that the performance of the QPSK-OFDM system that invokes the CAZAC preamble achieved a further SNR gain of about 2 dB via cooperative transmission. Therefore, the QPSK-OFDM system benefited both from the employment of CAZAC preamble as time synchronization preamble, as well as, the relay-aided cooperative transmission in the SUI-5 channel. This is because the SUI-5 channel is type A terrain which, is a highly fading channel.

B. ADAPTIVE MODULATION RESULTS AND DISCUSSION
This section presents the performance of the AM-CAZAC-OFDM cooperative system, as seen in Fig. 1 in terms of BER and channel throughput when communicating over SUI-5 channel.

The CAZAC-OFDM cooperative system with adaptive modulation that employs the CAZAC preamble-based SNR estimator is referred to as the AM-CAZAC-OFDM scheme. The performance of the AM-CAZAC-OFDM cooperative scheme is comparatively studied against the CAZAC-OFDM cooperative system with fixed modulation of M-PSK and M-QAM, which dispenses adaptive modulation. The proposed AM-CAZAC-OFDM scheme is also evaluated against the AM-Schmidl-OFDM benchmark scheme.
The corresponding channel throughput performance is shown in Fig. 17. The employment of the CAZAC SNR estimator provided significant improvement by about 4 dB in terms of channel throughput versus actual SNR performance compared to the AM-Schmidl-OFDM cooperative scheme when targeting at channel throughput of 4.5 bps/Hz. Moreover, the employment of the CAZAC SNR estimator in the AM-CAZAC-OFDM cooperative system significantly improved the channel throughput in comparison with the CAZAC-OFDM cooperative dispensing with adaptive modulation.

Similar observations may be made for the AM-CAZAC-OFDM cooperative system that employs $M$-QAM with a switching threshold of Table 2. It can be seen from Fig. 18 that the BER performance of the AM-CAZAC-OFDM scheme outperforms the CAZAC-OFDM cooperative scheme with fixed modulation of $M$-QAM. More specifically, the AM-CAZAC-OFDM scheme that invokes $M$-QAM outperforms the CAZAC-OFDM cooperative system dispensing with adaptive modulation that invokes 8-QAM by about 5 dB at BER $= 10^{-3}$ when communicating over SUI-5 channel. Moreover, the AM-CAZAC-OFDM cooperative system outperforms the AM-Schmidl-OFDM benchmark scheme by about 0.5 dB at BER $= 5 \times 10^{-3}$.

The corresponding channel throughput versus actual SNR performance is shown in Fig. 19. It can be observed that the employment of the CAZAC preamble-based SNR estimator provided modest improvement by about 1 dB in terms of channel throughput compared to the AM-Schmidle-OFDM cooperative scheme when targeting at channel throughput of 4.5 bps/Hz. However, the employment of the CAZAC SNR estimator in the AM-CAZAC-OFDM cooperative system improved the channel throughput in comparison with the CAZAC-OFDM cooperative dispensing with adaptive modulation. Additionally, it was found that an improved channel throughput is achieved in the AM-CAZAC-OFDM
FIGURE 19. Channel throughput performance of AM-CAZAC-OFDM cooperative system with adaptive modulation that invokes \(M\)-QAM over SUI-5 channel.

FIGURE 20. BER performance of AM-CAZAC-OFDM scheme exploiting cooperative transmission that invokes \(M\)-PSK over SUI-5 channel.

V. CONCLUSION

In this paper, an adaptive modulation in SISO-OFDM-based cooperative system that employs the CAZAC preamble-based SNR estimator, was proposed. The proposed AM-CAZAC-OFDM cooperative scheme benefited from the employment of the CAZAC preamble owing to its two-fold roles as time synchronization preamble and SNR estimator. The CAZAC preamble-based SNR estimator exhibited less than 0.02 dB and less than 0.2 dB bias when communicating over AWGN and SUI-5 channels, respectively. The employment of the CAZAC SNR estimator in the AM-CAZAC-OFDM cooperative system demonstrated a beneficial improvement in terms of BER versus actual SNR compared with the AM-Schmidl-OFDM scheme exploiting Schmidl SNR estimator. Moreover, the proposed AM-CAZAC-OFDM scheme significantly improved the channel throughput in comparison with the CAZAC-OFDM scheme dispensing with adaptive modulation. More specifically, the AM-CAZAC-OFDM cooperative scheme that invokes \(M\)-PSK outperforms the CAZAC-OFDM cooperative scheme that invokes 8-PSK by about 5 dB at BER \(=10^{-3}\) when communicating over SUI-5 channel. It was observed that the relay-aided cooperative transmission in the proposed AM-CAZAC-OFDM cooperative scheme has resulted in further enhanced BER and channel throughput benefited from spatial diversity. The AM-CAZAC-OFDM scheme exploiting cooperative transmission exhibited an approximately 6 dB SNR gain in terms of channel throughput in comparison to the non-cooperative scheme.

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