

Cooperative Communication Between Cognitive and Primary Users

Wei Liang, Soon Xin Ng and Lajos Hanzo
School of ECS, University of Southampton, SO17 1BJ, UK.

Tel: +44-23-8059 3125, Fax: +44-23-8059 4508

Email: {wl7g09,sxn,lh}@ecs.soton.ac.uk, <http://www-mobile.ecs.soton.ac.uk>

Abstract

The active cooperation between a Primary User (PU) and a Cognitive User (CU) has the potential of leading to a transmission power reduction and transmission rate increase for both the PU and the CU. Alternatively, the required bandwidth may be reduced and the freed bandwidth may be leased to a group of CUs for their secondary communications. More explicitly, our cooperative protocol allows a CU to serve as a Relay Node (RN) for relaying the signal of the first PU, which is a Source Node (SN), to the second PU, which is a Destination Node (DN). Furthermore, we conceived adaptive Turbo Trellis Coded Modulation (ATTCM) for appropriately adjusting both the code rate and the modulation mode according to the near-instantaneous channel conditions. The ATTCM switching thresholds specifically adjusted for ensuring that the Bit Error Ratio (BER) is below 10^{-5} in order to minimize the potential error propagation from the RN to the DN. It was found that the joint design of coding, modulation, user-cooperation and Cognitive Radio (CR) techniques may lead to significant mutual benefits for both the PUs and the CUs. More specifically, we propose an ATTCM aided two-way relaying cooperative CR scheme that maximizes the CU's own data rate and improves the exploitation of the bandwidth released by the PUs. Our numerical and simulation results show that the bandwidth reduction attained by the proposed two-way relay based CR scheme is more than 80% of the PU's bandwidth.

Index Terms

Cognitive Radio Network, Cooperative Communication, Relay selection, two-way relay, ATTCM

I. INTRODUCTION

Cognitive Radio (CR), relying on a software-defined radio, is an emerging technology that enables the flexible development, construction, production, shipping and deployment of highly adaptive radios [1]. The two primary CR objectives defined in Haykin's paper [2] are:

- Highly reliable communication whenever and wherever needed;
- Efficient utilization of the radio spectrum.

The CR mechanism is also capable of exploiting the available spectrum holes in the communication spectrum. If the spectrum is not used by the Primary Users (PUs), then the Cognitive Users (CUs) would have the opportunity to access it for their secondary communications based on the CR technique. According to the CR protocol, the device listens to the wireless channel and identifies the spectrum holes, either in the time or in the frequency domain [1], [3], [4]. Moreover, the most common paradigms associated with cognitive radios are the so-called underlay, overlay and interweave networks. In the underlay paradigm, the CUs communicate with the aid of the PUs under the constraint that the interference imposed by the CUs on the PUs must not degrade the PUs' communication quality. In contrast to the underlay scheme, the CUs in the interweave paradigm can only transmit simultaneously with a PU in the event of a false spectral hole detection. Thus in effect, the CU's transmit power is limited by the sensing-range of its spectral hole sensing, not by the interference experienced. Moreover, in the overlay paradigm, both the CU and PU communicate using the same frequency band in the same geographic space, assuming that the CUs assist the PUs' transmissions invoking cooperative communication techniques, such as advanced coding or cognitive relaying techniques [5], [6].

Cooperative communication [7] is a new communication paradigm that promises significant capacity and multiplexing gain improvement in wireless networks. It is capable of supporting users by providing an improved integrity or throughput with the advent of user cooperation [8]. The two most popular collaborative protocols are the Decode-And-Forward (DAF) and the Amplify-And-Forward (AAF) schemes [9]. Cooperative communication aided CR systems may be categorized into the following three types: 1) cooperation among the PUs; 2) cooperation between PUs and CUs; 3) cooperation among the CU peers [10]. More specifically, the first type is similar to traditional cooperative communication. In the third type, a CU may act as a RN for other CUs, which may have different available spectra [10]. For the second type, the PUs have a higher priority than the CUs, where the CUs may act as RNs for PUs [11], [12]. More specifically, the active cooperation [11] among the PUs and CUs would allow the PUs to transmit at a lower power and/or at a higher throughput, while at the same time enabling

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the CUs to communicate using the released bandwidth. Another interesting protocol involving simultaneous transmissions of the PUs and CUs has been proposed in [4] for maximizing the overall achievable rate.

In our work, we consider a cooperative CR scheme, which relies on cooperation of the source PU and the destination PU with the aid of the CUs acting as RNs. This is commonly referred to as the overlay paradigm, and various papers have focused on this model, when appointing a single PU [13], [14]. However, in these scenarios the PU's improved performance does not necessarily translate into a satisfactory performance for the CUs. In some cases, the CUs have limited spectrum access opportunities, if the PUs have their own data to transmit [14]. In our approach, we aim for increasing the CU's own data rate by exploiting the bandwidth released by the PUs, as well as increasing the throughput of PUs by using one of these CUs as a RN. In our proposed one-way relay aided cooperative CR system, we have considered multiple CUs and a single PU. We have employed the relay selection technique of [15] for choosing the best CU to act as a RN in order to help the PU to successfully deliver its information. Moreover, we have also proposed a novel two-way relay aided cooperative CR scheme, which has two PUs in the system. We have considered two protocols in this scenario. The first protocol is based on a Time Division Broadcast Channel (TDBC) [16], which relies on three time slots. The second protocol is based on a Multiple-Access Broadcast Channel (MABC) [16], which requires only two time slots. In this contribution, we design coding and modulation schemes for an active cooperation based CR system.

In CR systems the link-quality varies across a wide range, which cannot be adjusted by power-control. Hence near-instantaneously adaptive coded modulation is proposed, which is capable of accommodating these differences. We have considered the idealistic adaptive schemes based on both the Continuous-input Continuous-output Memoryless Channel (CCMC) and on the Discrete-input Continuous-output Memoryless Channel (DCMC) [17]. More specifically, the CCMC based adaptive scheme assumes that idealistic capacity-achieving coding and modulation schemes are employed for communicating exactly at Shannon's capacity. By contrast, the DCMC based adaptive scheme assumes that an idealistic capacity-achieving code is employed for aiding the PSK/QAM modulation schemes considered for the sake of operating right at the modulation-dependent DCMC capacity. Furthermore, we also considered a practical adaptive scheme based on power- and bandwidth-efficient Turbo Trellis Coded Modulation (TTCM) [18], which is a joint coding and modulation scheme that has a structure similar to binary turbo codes. Additionally, the TTCM schemes [19] were designed based on the best component Trellis Coded Modulation [20] components using the so-called 'punctured' minimal distance criterion for communicating over the Additive White Gaussian Noise (AWGN) channel. The transmission rate/throughput (or information Bit-per-Symbol (iBPS)) of our system is adapted according to the instantaneous channel conditions. A higher-throughput TTCM scheme is employed when the channel conditions are good, while a lower-throughput TTCM scheme or no transmission is used, when the channel conditions are poor.

The novel contributions of our paper are:

- The CUs' data rate is maximized by our proposed cooperative CR scheme. Similarly, the PU is also capable of transmitting at an improved transmission rate at a given SNR, while releasing a significant amount of its bandwidth for exploitation by the CUs.
- We conceive a two-way relaying scheme for our proposed CR system based on both the TDBC and the MABC protocols, which aims for jointly improving the power efficiency, the achievable rate and the throughput of PUs.
- A practical adaptive coded modulation scheme is investigated and benchmarked against idealistic adaptive schemes.

The rest of the paper is organized as follows. The system design of the idealistic cooperative CR scheme capable of operating at exactly Shannon's capacity is outlined in Section II-A. The fixed modulation based transmission model of our cooperative CR scheme is detailed in Section II-B, while our realistic ATTCM-aided one-way relaying system is described in Section II-C.2. The details of our ATTCM-aided two-way relaying assisted cooperative CR schemes are provided in Section II-C.3. The overall performance of our proposed schemes is evaluated in Section III, while our conclusions are presented in Section IV.

II. SYSTEM MODEL

A. System Design of our Idealistic Cooperative Cognitive Radio Scheme

In this section, we adopt the cooperative CR philosophy of [11], [12] relying on the cooperation between a PU (as the source node (SN)) and a CU (as the relay node (RN)) for conveying the source message to another PU (as the destination node (DN)). To facilitate efficient spectrum sharing between the PU and CUs, we consider configuring and sharing the frequency bands of W_1 and W_2 , as shown in Fig. 1. Observe in Fig. 1 that the CU acts as a RN and assists the PU in transmitting its signal in one of the frequency bands, namely in W_1 . In the other frequency band, namely W_2 , the PU remains silent and the CUs transmit their own signals by using the entire time slot T .

Again, Fig. 1 illustrates the bandwidth, time period and power allocation for the PU and CUs, where T and W_0 are the original time period and bandwidth allocated for the PU/SN¹ to transmit its source message to the PU/DN. When the PU/SN is assisted by a CU/RN, the PU/SN only has to utilize a fraction of T and W_0 in order to convey the source message to the PU/DN. More specifically, the PU/SN and CU/RN will share the bandwidth W_1 to convey the source message to the PU/DN,

¹We represent the PU acting as the source node as PU/SN. Similarly, CU/RN denotes the CU acting as a relay node, while PU/DN denotes the PU acting as the destination node.

while the other CUs may use the remaining bandwidth of ($W_2 = W_0 - W_1$) for their own communications. In other words, a CU/RN assists in saving some of the transmission power of the PU/SN due to the reduction of the transmission period from T to T_1 . In return, the PU/SN would release the bandwidth W_2 to other CUs. More specifically, let us assume that the transmission power per unit frequency emanating from the PU/SN is P_S watts/Hz and the target transmission rate is R_{pu} bits/s. The PU/SN transmits using the power of P_S during T_1 , while the CU/RN forwards the source message using the power of $P_{CR,1}$ during T_2 and the second CU can broadcast its message to other CUs using the power of $P_{CR,2}$ during the entire time period T .

During the first time slot T_1 , the PU/SN broadcasts the source message x to both the CU/RN and the PU/DN. The signal received at the PU/DN via the Source-to-Destination (SD) ² link is given by:

$$y_{sd} = \sqrt{P_S} h_{sd} x + n_{sd} , \quad (1)$$

and the signal received at the CU/RN via source-to-relay (SR) link is:

$$y_{sr} = \sqrt{P_S} h_{sr} x + n_{sr} , \quad (2)$$

where n_{sd} and n_{sr} are the AWGN processes having an average single-sided noise power per unit frequency of $N_0 = 4.0 \times 10^{-21}$ watts/Hz [11] in the SD and SR links, respectively. In this contribution, we have adopted the AAF model of [11] and additionally we extended it to our DAF model. Hence our CU/RN is capable of caring out either the AAF or the DAF operation.

During the second time slot T_2 the CU/RN would forward the source message to the PU/DN using the transmission power of $P_{CR,1}$ watts/Hz. When considering the DAF protocol, provided that the RN is capable of decoding the transmitted symbol correctly, it forwards the decoded symbol with a power $P_{CR,1}$ to the DN. Otherwise the RN remains idle. The signal received by the PU/DN via the relay-to-destination (RD) link may be formulated as:

$$y_{rd}^{DAF} = \sqrt{P_{CR,1}} h_{rd} x + n_{rd} . \quad (3)$$

Similarly, when considering the AAF cooperation protocol, the CU/RN amplifies the received signal and forwards it to the PU/DN at a transmit power of $P_{CR,1}$. The signal received by the PU/DN via the RD link may be expressed as:

$$y_{rd}^{AAF} = \omega_A \sqrt{P_{CR,1}} h_{rd} y_{sr} + n_{rd} , \quad (4)$$

where $\omega_A = \frac{1}{\sqrt{P_S |h_{sr}|^2 + N_0}}$ [21] is the amplification factor. Then the signal received by the PU/DN under the AAF protocol via the RD link may be rewritten as

$$\begin{aligned} y_{rd}^{AAF} &= \frac{\sqrt{P_{CR,1}} h_{rd} y_{sr}}{\sqrt{P_S |h_{sr}|^2 + N_0}} + n_{rd} , \\ &= \frac{\sqrt{P_{CR,1}} P_S h_{rd} h_{sr}}{\sqrt{P_S |h_{sr}|^2 + N_0}} x + \frac{\sqrt{P_{CR,1}} h_{rd}}{\sqrt{P_S |h_{sr}|^2 + N_0}} n_{sr} + n_{rd} . \end{aligned} \quad (5)$$

The channel gains h_{sd} , h_{sr} and h_{rd} are assumed to be independent complex Gaussian random variables with zero mean and variances of σ_{sd}^2 , σ_{sr}^2 and σ_{rd}^2 , respectively. The channel variance is [21], [22]: $\sigma_{ab} = \left(\frac{\lambda}{4d_{ab}\pi} \right)^\alpha = \left(\frac{c}{4d_{ab}f_c\pi} \right)^\alpha$. Where d_{ab} denotes the geometrical distance between node a and node b , the wavelength is $\lambda = \frac{c}{f_c}$, where c is the speed of light and we consider a carrier frequency of $f_c = 350$ MHz. Furthermore we consider an outdoor environment, where the path-loss exponent [23] is given by $\alpha = 3$.

In our scheme, the PU/SN transmits during T_1 , while the CU/RN transmits during T_2 . Both the PU/SN and CU/RN utilize the bandwidth W_1 . When the AAF protocol is employed based on Shannon's capacity theorem, the CCMC capacity of the cooperative relay channel over the bandwidth of W_1 Hz is given by:

$$C_{PU}^{AAF} = \frac{W_1}{2} \log_2 \left[1 + \frac{P_S |h_{sd}|^2}{N_0} + f_{CR} \right] , \quad (6)$$

where we have [21, pg. 122]: $f_{CR} = \frac{P_S P_{CR,1} |h_{sr}|^2 |h_{rd}|^2}{(P_S |h_{sr}|^2 + P_{CR,1} |h_{rd}|^2 + N_0) N_0}$. When we consider the DAF protocol, the capacity of our system is limited by the capacity of either the SR link or that of the combined channel constituted by the SD and RD links which ever is lower. Then the CCMC capacity of DAF transmissions over W_1 Hz can be formulated as [21, pg. 126]:

$$C_{PU}^{DAF} = \frac{W_1}{2} \min \left[\log_2 \left(1 + \frac{P_S |h_{sd}|^2}{N_0} + \frac{P_{CR,1} |h_{rd}|^2}{N_0} \right), \log_2 \left(1 + \frac{P_S |h_{sr}|^2}{N_0} \right) \right] , \quad (7)$$

²The SD link is represented by the link between the PU/SN and the PU/DN. The SR link represents the communication link between the PU/SN and the CU/RN. Additionally, the communication link between the CU/RN and the PU/DN is referred to as the RD link.

The factor $\frac{1}{2}$ in Eq. (6) and Eq. (7) indicates that the PU only utilizes the first time slot T_1 of Fig. 1, which the CU uses the second time slot T_2 to transmit its signals. Without loss of generality, we assume $T_1 = T_2 = \frac{T}{2}$. Based on Eq. (6), the bandwidth required for achieving a transmission rate of $R_{PU} \leq C_{PU}^{AAF}$ may be formulated as:

$$W_1 \geq \frac{2R_{PU}}{\log_2 \left[1 + \frac{P_S|h_{sd}|^2}{N_0} + \frac{P_S P_{CR,1}|h_{sr}|^2|h_{rd}|^2}{(P_S|h_{sr}|^2 + P_{CR,1}|h_{rd}|^2 + N_0)N_0} \right]}. \quad (8)$$

For the DAF protocol, the bandwidth requirement of W_1 can be expressed as:

$$W_1 \geq \frac{2R_{PU}}{\min \left[\log_2 \left(1 + \frac{P_S|h_{sd}|^2}{N_0} + \frac{P_{CR,1}|h_{rd}|^2}{N_0} \right), \log_2 \left(1 + \frac{P_S|h_{sr}|^2}{N_0} \right) \right]}. \quad (9)$$

In the non-cooperative case, the CCMC capacity of the PU/SN is given by:

$$C_{PU}^* = W_0 \log_2 \left[1 + \frac{P_{PU}|h_{sd}|^2}{N_0} \right]. \quad (10)$$

For the following derivation, we use the C_{PU} to represent C_{PU}^{DAF} and C_{PU}^{AAF} . It can be shown that the transmission power originally required for achieving $R_{PU} = C_{PU}$ is given by:

$$P_{PU} = \frac{N_0(2^{\frac{R_{PU}}{W_0}} - 1)}{|h_{sd}|^2}. \quad (11)$$

As seen in Fig. 1, a group of CUs is capable of communicating using the released bandwidth W_2 for the entire period of T , while a CU is helping the PU/SN as a RN. The received signal for CUs to transmit its own signal in the whole time slot T is given by:

$$y_{CR} = \sqrt{P_{CR,2}}h_{CR}x_{CR} + n_{CR}, \quad (12)$$

where h_{CR} denotes the channel between a CU's transmitter (CU/SN) and its destination (CU/DN) for its own transmission. The source message x_{CR} transmit from CU/SN to CU/DN and n_{CR} is the AWGN process. Then, the achievable transmission rate of the CUs is given by:

$$R_{CR} = W_2 \log_2 \left[1 + \frac{P_{CR,2}|h_{CR}|^2}{N_0} \right], \quad (13)$$

If the total transmission power of CUs is limited to P_{CR} , then we have:

$$P_{CR} = \frac{1}{2}P_{CR,1}W_1 + P_{CR,2}W_2. \quad (14)$$

In this way, the CUs can decide how to allocate their joint transmission power in order to maximize their own data rate. Let us define the ratio of transmission power allocated for helping the PU/SN to the total transmission power of the CUs over the bandwidth W_1 as:

$$\psi = \frac{\frac{1}{2}P_{CR,1}W_1}{P_{CR}}, \quad (15)$$

where $\psi = [0 \ 1]$. Similarly, the ratio of the transmission power allocated to transmit the CUs' data to the total transmission power of the CUs, over the bandwidth W_2 can be defined as:

$$1 - \psi = \frac{P_{CR,2}W_2}{P_{CR}}. \quad (16)$$

More specifically, the transmission power $P_{CR,1}$ at CU/RN may be determined from Eq. (9) and Eq. (15). On the other hand, the CU's own data rate using the released bandwidth $W_2 = W_0 - W_1$ may be derived as :

$$R_{CR} = (W_0 - W_1) \log_2 \left[1 + \frac{P_{CR}|h_{CR}|^2(1 - \psi)}{(W_0 - W_1)N_0} \right], \quad (17)$$

which can be optimized with respect to ψ . Moreover, the Reduced-Distance-Related-Pathloss-Reduction (RDRPR) [24], [25] experienced in our system by the SD, SR and RD links with respect to the SD link as a benefit of its reduced distance based path-loss can be expressed as [24]: $G_{sd} = (\frac{d_{sd}}{d_{sd}})^3$, $G_{sr} = (\frac{d_{sd}}{d_{sr}})^3$ and $G_{rd} = (\frac{d_{sd}}{d_{rd}})^3$ respectively. Naturally, the RDRPR of the SD link with respect to itself is unity, i.e. we have $G_{sd} = 1$. Our quantitative results for the AAF and DAF aided cooperative CR scheme will be discussed in Section III-A.

B. Fixed-mode Transmission in Cooperative Cognitive Radio Schemes

In this section, we investigate the achievable bandwidth reduction based on three fix-mode transmission schemes. More specifically, System A in Fig. 2 is a non-cooperative system, while System B and System C are relay aided cooperative CR systems. We assume that both the SN and the DN are PUs and the RN is a CU. The passband bandwidth ζ of PSK/QAM modulation is assumed to be the same as the Baud-rate (or symbol rate) of R_s symbol/s, while the baseband bandwidth is given by $R_s/2$ symbol/s, when an ideal lowpass filter is assumed. The bit rate of the system is $R_b = \eta \times R_s$ (bit/s), where η is the throughput in bit-per-symbol (bps). When considering a pathloss exponent of $\alpha = 3$, we have a RDRPR of $G = 2^\alpha = 8$, which is $\tilde{G} = 10 \log_{10}(8) = 9$ dB when the RN is located at the mid-point between the SN and the DN. The received SNR (SNR_r) in decibel is given by:

$$\text{SNR}_r = \text{SNR}_t + \tilde{G}. \quad (18)$$

and the transmit SNR³ is $\text{SNR}_t = 10 \log_{10}(\frac{P_t}{N_0})$, where P_t is the transmit power and N_0 is the single-sided noise power. We assume that a BER of 10^{-5} or less is required at the DN, where received SNRs of 9dBs and 18dBs are required at the DN, when TTCM-8PSK and TTCM-64QAM are employed, respectively. The SD link is assumed to be of low quality and hence it is not considered in this example.

As seen from Fig. 2, the PU/SN of System B is capable of increasing its throughput to $\eta_B = 2.5$ bps from the $\eta_A = 2$ bps value of System A, when using the same bandwidth of $\zeta = R_s$. Their bit rate rate is $\frac{R_b^A}{R_b^B} = \frac{2R_s^A}{2.5R_s^B}$ upon assuming that System A and System B have the same symbol rate of $R_s^A = R_s^B$, the relationship of their bit rate is given by:

$$\begin{aligned} R_b^B &= \frac{\eta_B}{\eta_A} R_b^A, \\ &= 1.25 R_b^A. \end{aligned} \quad (19)$$

Thus, System B has a 25% higher bit rate than System A within the same bandwidth. Then the relationship between the bit rate of System B and symbol rate of System A is $R_b^B = 1.25 R_b^A = 1.25 \times 2 R_s^A = 2.5 R_s^A$.

By contrast, both System A and System C have the same bit rate of $R_b^A = R_b^C$, while the relationship of their symbol rates is given by:

$$\begin{aligned} R_s^C &= \frac{\eta_A R_s^A}{\eta_C}, \\ &= 0.8 R_s^A. \end{aligned} \quad (20)$$

Hence, System C is capable of providing the same bit rate using only 80% of the original bandwidth. This is achieved at a lower Baud-rate of $p R_s$, where $p = \frac{\eta_A}{\eta_C} = \frac{2}{2.5} = 0.8$ is the throughput ratio of System A to System C. Then the relationship between the bit rate of System C and the symbol rate of System A is $R_b^C = 2 R_s^A$.

More specifically, the bandwidth-reduction factor is given by:

$$B_s = 1 - \frac{\eta_A}{\eta_C}. \quad (21)$$

Therefore, a CU assist in PU's transmission could save 20% ($1 - 0.8 = 0.2 = 20\%$) of PU's bandwidth. Thus, this saved bandwidth can then be shared among other CUs. If we create a System D in a practical approaches where the bit rate of PU is lower than that of System B, but higher than that of System A, then we have $R_b^D = 1.1 R_b^A$. By referring to Fig. 2, we have $\eta_A = 2.0$ bps and $\eta_D = 2.5$ bps. Furthermore, we have $R_b^D = 1.1 \eta_A \times R_s^A = 1.1 \times 2 \times R_s^A = 2.2 \times R_s^A$. Based on Eq. (20), we have $R_s^D = \frac{\eta_A R_s^A}{\eta_D} = \frac{2.2}{2.5} R_s^A = 0.88 R_s^A$. Then the bandwidth-reduction factor becomes $B_s = 1 - \frac{\eta_A}{\eta_D} = 1 - 0.88 = 0.12$. In this situation, System D is capable of reducing the original bandwidth by 12% for the CU's benefit, while the PU enjoys an additional 0.5 bps throughput increment.

C. Practical ATTCM-aided Cooperative Cognitive Radios

We have shown that it is possible and practical for the PU to release the available bandwidth for supporting the CU's own transmission in exchange for an increased transmission throughput based on the analysis of Section II-B. In this section, ATTCM aided one-way and two-way relaying schemes are proposed for cooperative CR applications.

³The concept of transmit SNR [25] is unconventional, as it relates quantities to each other at two physically different locations, namely the transmit power to the noise power at the receiver, which are at physically different locations.

1) *The ATTCM Algorithm:* In our proposed system, we will make use of this power- and bandwidth-efficient TTCM scheme. Employing TTCM has the advantage that the system's effective throughput can be increased upon increasing the code rate, when the channel-quality improves. Additionally, both the BER and Frame error ratio (FER) performance of the system may be improved when TTCM is used [26]. Recently, various TTCM schemes were designed in [27] with the aid of the Extrinsic Information Transfer (EXIT) charts [28], [29] and union bounds for the sake of approaching the capacity of the Rayleigh fading channel. The TTCM encoder comprises two identical parallel-concatenated TCM encoders [20] linked by a symbol interleaver. The first TCM encoder directly processes the original input bit sequence, while the second TCM encoder manipulates the interleaved version of the input bit sequence. Then the bit-to-symbol mapper maps the input bits to complex-valued symbols using the Set Partition (SP)-based labelling method [26]. The structure of the TTCM decoder is similar to that of binary turbo codes, but each decoder alternately processes its corresponding encoder's channel-impaired output symbol, and then the other encoder's channel-impaired output symbol [26, pg.764]. More details on the TTCM principles may be found in [26]. We have employed a ATTCM scheme for protecting the SR and the RD links, where the effective throughput (or information Bit-per-Symbol (iBPS)) range is given by $iBPS = \{0, 1, 2, 3, 5\}$ bps when no transmission, QPSK, 8PSK, 16QAM and 64QAM are considered, respectively.

Moreover, the ATTCM mode switching thresholds $\Upsilon = [\gamma_0, \gamma_1, \gamma_2, \gamma_3]$ are determined based on the BER performance curves of each of the four TTCM schemes communicating over Rayleigh channels, as shown in Fig. 3. Specifically, we consider the five TTCM modes and the ATTCM mode switching operation based on the following algorithm:

$$\text{MODE} = \begin{cases} \gamma_R > \gamma_3, & \text{TTCM-64QAM, BPS=5bps;} \\ \gamma_2 < \gamma_R \leq \gamma_3, & \text{TTCM-16QAM, BPS=3bps;} \\ \gamma_1 < \gamma_R \leq \gamma_2, & \text{TTCM-8PSK, BPS=2bps;} \\ \gamma_0 < \gamma_R \leq \gamma_1, & \text{TTCM-4PSK, BPS=1bps;} \\ \gamma_R \leq \gamma_0, & \text{No-Tx, BPS=0bps;} \end{cases}$$

2) *One-way Relaying aided Cooperative CR scheme:* As shown in Fig. 1, we consider a single SN, K RNs, and a single DN. All relays operate in the half-duplex DF mode and it is assumed that each relay only knows its own channel, but the DN receiver knows all channel value with the aid of training. In addition, the benefit of the direct SD link is also considered. The signal received by node b from node a is given by:

$$y_{ab} = \sqrt{G_{ab}}\sqrt{P_{ab}}h_{ab}x + n, \quad (22)$$

where G_{ab} denotes the RDRPR experienced by the link between node a and node b , while h_{ab} represents the symmetric quasi-static Rayleigh fading channel gain of the ab link and we assume that all channel gains are independent of each other. The quasi-static Rayleigh fading channels between the SN and the RNs are denoted as $\{h_{sr_k}\}_{k=1}^K$, while those between the RNs and the DN are represented by $\{h_{r_kd}\}_{k=1}^K$. The power term P_{ab} is normalized to unity. We use the notation γ_{ab} to refer to the instantaneous receive SNR of the link between node a and node b , so that $\gamma_{ab} = \frac{G_{ab}|h_{ab}|^2}{N_0}$.

Among these K available relays only the specific relay with the highest instantaneous SNR is selected for forwarding the signal transmitted from the SN to the DN. The channel condition $|h_{sr_i}|, |h_{r_id}|$, at each relay, which has included G_{ab} , describes the quality of the SR and RD links, when using the i th RN. The capacity of this two-hop scheme is limited by the particular hop that has the minimum SNR or $\{\min[|h_{sr_i}|^2, |h_{r_id}|^2]\}$, which is also referred to as "bottleneck" [15]. We have $(K + 1)$ links spanning from the SN to the DN supported by K RNs as well as the SD link. We have considered the max-min relay selection technique for maximizing the transmission rate, which relies on the policy defined as [30]:

$$k = \arg \max_i \{ \min[|h_{sr_i}|^2, |h_{r_id}|^2] \}. \quad (23)$$

Under this policy, the best RN imposes the most restrictive "bottleneck" among the RNs. We have considered a Single-Input-Single-Output (SISO) [31] system for both the SR and RD link in our one-way relay system, where each node has one antenna, and employed maximum likelihood (ML) Multiuser Detection (MUD). The ML MUD provides the best possible performance at the cost of the highest complexity, which is a non-linear detector, and it is optimal in terms of minimizing the symbol error probability, when all possible vectors are equally likely [32]. In our proposed system we have considered perfect channel estimation. In the non-cooperative scheme of System A, $|h_{sd}|^2$ is used for computing the SNR_r. Additionally, all cognitive relays are located near the centre of the system, hence we have $G_{sr} = G_{rd} = 8$. As we discussed in Section II-C.1, each of our communication links is assisted by the ATTCM scheme. As seen from Fig. 3, we specifically chose the switching thresholds for ensuring that the BER at the RN became lower than 10^{-5} , which are given by $\Upsilon_{ATTCM} = [6.5, 15.5, 22, 35.8]$ dB. We note that Shannon's CCMC capacity is only restricted by the SNR and the bandwidth. The CCMC-based (perfect-code-related) switching thresholds are represented as $\Upsilon_{CCMC} = [1.75, 6, 11, 14]$ dB, while the switching thresholds of the corresponding DCMC based scheme are given by $\Upsilon_{DCMC} = [2, 8, 12.5, 20]$ dB, which are also explicitly shown in Fig. 3.

Although the Systems B, C and D introduced in Section II-B are all relay-aided cooperative CR schemes, we have had different design objectives for their bit rate and symbol rate. Hence, they also illustrate the different benefits of cooperative CR

networks. Let us now refer to Fig. 5(a) and Fig. 5(b), where we consider ATTCM instead of fixed-mode 8PSK and 64QAM. The system labelled as ATTCM-SystemA is the classic non-cooperative scheme, while ATTCM-SystemB, ATTCM-SystemC and ATTCM-SystemD are all relay-aided cooperative CR schemes. ATTCM-SystemB achieves a higher bit rate by invoking user-cooperation within the same bandwidth, as ATTCM-SystemA. By contrast, ATTCM-SystemC achieves a higher bandwidth reduction by employing user-cooperation, while maintaining the same bit rate as ATTCM-SystemA. Furthermore, ATTCM-SystemD achieved both a practical bit rate improvement as well as a bandwidth reduction. For the future implementation and investigation, we could also use the other coding schemes including LDPC instead of TTCM.

3) *Two-way Relaying aided Cooperative CR scheme*: Having studied the ATTCM aided one-way relaying assisted cooperative CR scheme in Section II-C.2, we will now consider how the one-way relay system may be extended to a two-way relaying assisted cooperative CR system, where the two PUs act as the SNs and the DNs for each other.

We have considered two protocols in our proposed scheme namely the TDBC and MABC. In the TDBC protocol shown in Fig. 4, there is no interference hence the corresponding complexity at the RN is kept low. Three time slots are used for two data flows, which are $s_1 \rightarrow r$, $s_2 \rightarrow r$, and $s_1 \leftarrow r \rightarrow s_2$, where s_1 and s_2 denote the two primary sources, while r denotes the CU which acts as a RN. By contrast, the MABC protocol requires two time slots for transmitting two data flows, which are $s_1 \rightarrow r \leftarrow s_2$ and $s_1 \leftarrow r \rightarrow s_2$. Since the sources transmit their information simultaneously, the MABC system suffers from self-interference. In our paper, we have invoked an advanced MUD technique at the RN in order to decode both information streams of the SNs and to cancel the self-interference. Explicitly, in the MABC protocol, two signals were transmitted simultaneously from the two PU/SNs, where each PU has a single antenna. Additionally, we have used the powerful maximum likelihood MUD for detecting the two source signals using a single-antenna aided CU/RN, which constitutes a (2×1) -element Multiple-Input-Single-Output (MISO) [31] system for the SR links. This powerful MUD was required for eliminating avalanche-like error propagation at the RNs. However, opted for (1×1) -element SISO system for the RD link, where each DN employs a single antenna for detecting its wanted signal arriving from the RN. By contrast, in the TDBC protocol, we have a (1×1) -element SISO system in the two SR links and a single RD link, because the two SNs use two separate time periods for transmitting their information to the RN, respectively.

We have opted for appointing the best relay has the set of available K RNs that experience identically and independently distributed (i.i.d) fading. Then the selected best RN decodes and forwards the received signals to the intended destinations, namely to the PU/DN₁ and PU/DN₂, respectively, during the second cooperative transmission period. Hence, the overall system throughput becomes higher than that of a one-way relaying scheme, which requires two time slots for transmitting a single user's information. Again, each of the communication links is assisted by our ATTCM scheme. By referring to Eq. (22), the signal transmitted from the SNs to the k th RN in our MABC two-way relay system is given by:

$$y_{sr_k} = \sqrt{G_{sr_k}} \sqrt{P_{sr_k}} h_{sr_k} X + n, \quad (24)$$

where X is a vector hosting both SNs' signal. We can view the two SNs as a combined two-antenna assisted SN, where Eq. (24) is a (2×1) -element MISO system. Furthermore, the signal received by the DNs from the RNs is given by:

$$y_{rkd} = \sqrt{G_{rkd}} \sqrt{P_{rkd}} h_{rkd} x + n, \quad (25)$$

where the RDRPR experienced by each link is defined as $G_{SR_1} = G_{SR_2} = G_{RD_1} = G_{RD_2} = 2^3 = 8$ in our system, since the RN is located midway between the SN and the DN. Additionally, the channel gains $h_{S_1R_k}$, $h_{S_2R_k}$, $h_{R_kD_1}$ and $h_{R_kD_2}$ are independent of each other, each of which is represented by a quasi-static Rayleigh fading channel. The Gaussian noise vector n has a zero mean and a noise variance of $N_0/2$ per dimension. By contrast, the SNR at the k th SR link is computed as:

$$\gamma_{(r, sr_k)} = \frac{G_{sr_k} |h_{sr_k}|^2}{N_0}. \quad (26)$$

Similarly, the SNR at the RD receiver is given by:

$$\gamma_{(r, rkd)} = \frac{G_{rkd} |h_{rkd}|^2}{N_0}. \quad (27)$$

Again, we have considered the max-min relay selection technique as defined in Eq. (23) for selecting the best RN.

The ATTCM-TDBC based switching thresholds were designed for ensuring that the BER at the RN becomes lower than 10^{-5} , which are represented as $\Upsilon_{ATTCM}^{TDBC} = [6.5, 15.5, 22, 35.8]$ dB, based on Fig. 3. Additionally, as seen from Fig. 3, we have chosen the ATTCM-MABC switching thresholds for ensuring that the BER at the RN became lower than 10^{-5} , which are given by: $\Upsilon_{ATTCM}^{(MABC, SR)} = [4.8, 12, 16, 24]$ dB and $\Upsilon_{ATTCM}^{(MABC, RD)} = [6.5, 15.5, 22, 35.8]$ dB. The reason why we have chosen the BER at the RN to be lower than 10^{-5} for the MABC protocol is because the error floor emerging at $BER < 10^{-5}$ can be removed by using a long outer code, such as a Reed Solomon Code. The performance of the TDBC and the MABC aided schemes is characterized in Section III-C.

III. PERFORMANCE RESULTS

A. The Performance of Idealistic Cooperative Cognitive Radio Schemes

The relationship of the power ratio ψ and the data rate of the CU is shown in Fig. 6(a) and Fig. 6(b). Fig. 6(a) illustrates the CU's own data rate with respect to the power ratio ψ , when the RDRPR factors are given by $G_{sd} = G_{rd} = 1$ and $G_{sr} = 8$. We assume that the total bandwidth is $W_0 = 1$ MHz and the target transmission rate of the PU/SN is $R_{PU} = 500$ Kbits/s. The total transmission power of the CU is $P_{CR} = 10$ dBm. In this system we assumed that the PU has maintained the same transmission power, which is $P_S = P_{PU}$ based on Eq.(11). Then, we plotted the data rate of the CU based on three different values of the distance d_{cr} between the CU and its own destination, namely for $d_{cr} = 500$ m, 1 km and 2 km. Finally, the optimum ratios of the relay power over the total power budget are given by 64.5%, 53% and 45% (with respect to $d_{cr} = 500$ m, 1 km and 2 km) when using the DAF protocol. Similarly, the optimum power ratios for the AAF protocol are given by 82%, 72% and 65%. As seen in Fig. 6(a), a CU/RN has offered a proportion of its transmission power to help the PU/SN, while $0 \leq \psi \leq 0.4$. During this period, the CU's own data rate is identical to zero. Fig. 6(b) shows the corresponding results when the RN is right in the middle of the PU/SN and PU/DN link, where the RDRPR factors are given by $G_{sd} = 1$ and $G_{sr} = G_{rd} = 8$. The optimum ratio of the relay power over the total power is 16%, 14% and 12% for $d_{cr} = 500$ m, 1 km and 2 km, respectively, when using DAF detection. Moreover, the corresponding values for AAF detection are given by 33%, 20% and 12%.

Observe in Fig. 6(a) and Fig. 6(b) that if the CU/RN is half-way between the SN and the DN, a CU/RN only has to dedicate a smaller proportion of its transmission power for aiding the PU/SN. Furthermore, as d_{cr} increases, the CU's own data rate drops due to its increased pathloss.

B. The Performance of One-way Relay Aided Cooperative Cognitive Radio Schemes

Fig. 7 shows the iBPS versus SNR_t performance of the ATTCM, CCMC and DCMC aided one-way relay schemes. As seen from Fig. 7, the curves recorded for the CCMC and DCMC modes are close to each other, when employing only one RN. For $SNR_t > 28$ dB, the iBPS value of the three system schemes became saturated at 5 bps. In general, the CCMC-SystemA and CCMC-SystemC arrangements represent the upper bound, because the CCMC capacity quantifies the highest throughput. As seen in Fig. 7, the intersection point of the ATTCM-SystemC and ATTCM-SystemA schemes is at $SNR_t = 8$ dB, while those for the CCMC-SystemC and CCMC-SystemA modes is at 1 dB and that for the DCMC mode is at 1.2 dB. At their intersection point, the throughput of System A and System C are equal. The throughput of the 'CCMC mode' is always better than that of the DCMC and ATTCM schemes. Additionally, the throughputs of all the System C is higher than those of the System A before their intersection point. Cooperation is no longer beneficial beyond the intersection point. Observe that when the number of RNs is increased to $K = 4$, the SystemC-related curves converge to the asymptotic value of 2.5 bps for $SNR_t > -8$ dB, which is 10 dBs earlier than their counterparts having $K = 1$. This is because when the number of RNs is increased, we have a higher chance of selecting a better RN for assisting the PU/SN.

Fig. 8 portrays the performance of the corresponding iBPS value versus SNR_t of the ATTCM, CCMC and DCMC aided one-way relay in the cooperative CR schemes, when communicating over quasi-static Rayleigh fading channels, in comparison to that of Shannon's capacity bound. We will refer to the CCMC capacity based curves as the upper bound. However, the DCMC capacity is more pertinent in the context of designing realistic channel-coded modulation schemes. Since we consider a RDRPR of $G_{sr} = G_{rd} = 8$, the curves of the one-way relay aided cooperative CR schemes are not within Shannon's capacity bound given for the Rayleigh channel. Additionally, the iBPS value of the CCMC, DCMC and ATTCM aided CR schemes saturated at 2.5 bps for $SNR_t = 11$ dB. If the RDRPRs are changed to $G_{sr} = G_{rd} = 1$, the resultant curves no longer exceed Shannon's capacity, where their iBPS curves saturated at 2.5 bps for $SNR_t = 20$ dB, which were shifted to the right by about 9 dB ($\log_{10}(2^3) = 9$ dB) with respect to those using $G_{sr} = G_{rd} = 8$. There are two transmission links in our one-way scheme, namely the SR link and the RD link. Based on our ATTCM mode switching thresholds, the system will activate the 64QAM mode for $\gamma_R > \gamma_3$. If both the SR and RD links have achieved their best performance associated with 64QAM, then the throughput of these two links becomes 5 bps. We have two time slots in our cooperative CR scheme, where both the SN and RN transmitted the same amount of information. Thus, our overall system throughput becomes $\eta_{SRD}^{one-way} = \frac{iBPS_{SR} + iBPS_{RD}}{2 \times \text{Timeslot}} = \frac{5+5}{2 \times 2} = 2.5$ BPS in the high-SNR region.

C. The Performance of Two-way Relay Aided Cooperative Cognitive Radio Systems

As seen in Fig. 9, both our proposed ATTCM aided MABC and TDBC two-way relay system have a higher throughput than the proposed one-way relay system, when we consider the same number of RNs in the one-way relay system. In the MABC two-way relay system, the iBPS value became saturated at 5 bps for $SNR_t \geq 11$ dB. The two SNs send their information simultaneously to a RN and then the RN broadcasts the combined information to the two DNs. The system throughput of the MABC two-way relay system is $\eta_{SRD}^{MABC} = \frac{iBPS_{S_1R} + iBPS_{S_2R} + iBPS_{R_1D} + iBPS_{R_2D}}{2 \times \text{Timeslot}} = \frac{5+5+5+5}{2 \times 2} = 5$ bps. When the MABC system has encountered the best possible channel conditions, the throughput became $\eta_{SRD}^{MABC} = \frac{5+5+5+5}{2 \times 2} = 5$ bps. Therefore, the asymptotic throughput of our proposed MABC two-way relay system ($\eta_{SRD}^{two-way}$) is twice that of the one-way relay scheme ($\eta_{SRD}^{one-way}$). By contrast,

the iBPS value of the TDBC two-way relay system became saturated at 3.3 bps for $\text{SNR}_t \geq 12$ dB. The TDBC two way relay system required three time slots, hence its η_{SRD} value is lower than that of the MABC scheme beyond $\text{SNR}_t = 1$ dB. The throughput of the TDBC two-way relay system is $\eta_{SRD}^{TDBC} = \frac{5+5+5+5}{2 \times 3} = 3.3$ bps, when each link has achieved its best condition. Moreover, its asymptotic throughput is 0.8 bps higher than the throughput of the one-way relay system. Fig. 9 shows the corresponding iBPS versus SNR_t performance of our proposed two-way relay system in comparison to the CCMC and DCMC capacity. Additionally, the curve of the MABC scheme are overlapped with the DCMC capacity for 32QAM at $\text{SNR}_t \geq 30$ dB.

Fig. 10 illustrates the attainable bandwidth-reduction (B_s) versus SNR_t for the ATTCM, the CCMC and the DCMC aided one-way relay as well as for the ATTCM-aided two-way relay schemes. As seen from Fig. 10, the attainable bandwidth-reduction B_s is slightly higher for the one-way relay scheme, when the number of RNs is increased from $K = 1$ to $K = 4$. It is also interesting to observe that the practical ATTCM scheme is capable of reducing the bandwidth more substantially compared to the idealistic DCMC and CCMC schemes. Furthermore, as the SNR increases, the bandwidth-reduction factor also reduces. This is because when the SNR is high, the quality of the SD link is sufficiently high for a fixed transmission throughput of 5 bps. The inclusion of a RN at high SNRs would only double the transmission period, without actually increasing the transmission throughput. Hence, we are only interested in the operational region, while we have $B_s > 0$. Note furthermore from Fig. 7 that at an SNR of 5 dB, the ATTCM-SystemA scheme can only achieve a throughput of 0.6 bps. However, with the aid of the best RN selected from four cooperating CUs, the ATTCM-SystemC would enable the PU to transmit at a throughput of 2.48 bps. This may also be translated into a maximum achievable bandwidth reduction of $(1 - \frac{0.6}{2.48}) = 0.758 = 75.8\%$. Fig. 10 also illustrates the attainable bandwidth-reduction (B_s) versus SNR_t for the ATTCM aided MABC and TDBC two-way relay system. Since we are only interested in the operational region of $B_s > 0$, for $\text{SNR}_t > 15$ dB, the proposed schemes relying on one-way relaying are no longer beneficial for the range of $B_s < 0$. The proposed two-way relaying scheme can use the entire bandwidth, since the bandwidth-reduction of the two-way relay scheme is always higher than zero. Observe from Fig. 7 that at an SNR_t of 5 dB, the ATTCM-SystemA scheme achieves a throughput of 0.6 bps. However, as seen in Fig. 10, the ATTCM-SystemC regime relying on TDMC two-way relaying would enable the PU to transmit at a throughput of 3.2 bps. Similarly, the ATTCM-SystemC relying on MABC two-way relaying would enable the PU to transmit at a throughput of 3.9 bps. This may be translated into a bandwidth reduction of $(1 - \frac{0.6}{3.2}) = 0.81 = 81\%$ for the TDBC scheme. In addition, it will lead to a bandwidth reduction of $(1 - \frac{0.6}{4.7}) = 0.87 = 87\%$ for the MABC scheme. Furthermore, the bandwidth reduction can be increased by $81 - 75.8 = 5.2\%$ upon employing the TDBC scheme compared to the one-way relay scheme. Additionally, $87 - 75.8 = 11.2\%$ bandwidth reduction can be attained by employing the MABC scheme in comparison to the one-way relay system. Moreover, at a given SNR, the two-way relay-aided system always attains a higher B_s value, than the corresponding one-way relay system.

IV. CONCLUSIONS

In this contribution, we have studied DAF and AAF assisted active cooperative CR schemes and quantified the optimum power ratio required for achieving the best transmission throughput for the CU. We proposed a practical ATTCM aided one-way relaying CR scheme, where adaptive coding and modulation were invoked according to the instantaneous channel conditions. We found that the proposed one-way CR scheme enables the PU to transmit at an improved transmission rate for a given SNR, while releasing a significant amount of bandwidth for exploitation by the CUs, despite operating at a reduced SNR. In the process of implementing the ATTCM aided one-way relaying CR scheme, we have also considered the max-min relay selection technique in order to choose the best relay for relaying the transmitted information from the SNs. Furthermore, in order to maximize the CU's own data rate and to improve the exploitation of the bandwidth released by the PUs, we also proposed a ATTCM aided two-way relay CR scheme by employing the MABC and TDBC protocols. The simulation results demonstrated that the two-way relay aided CR scheme is capable of achieving a higher bandwidth reduction than one-way relay aided CR scheme as well as simultaneously improving the system's average throughput.

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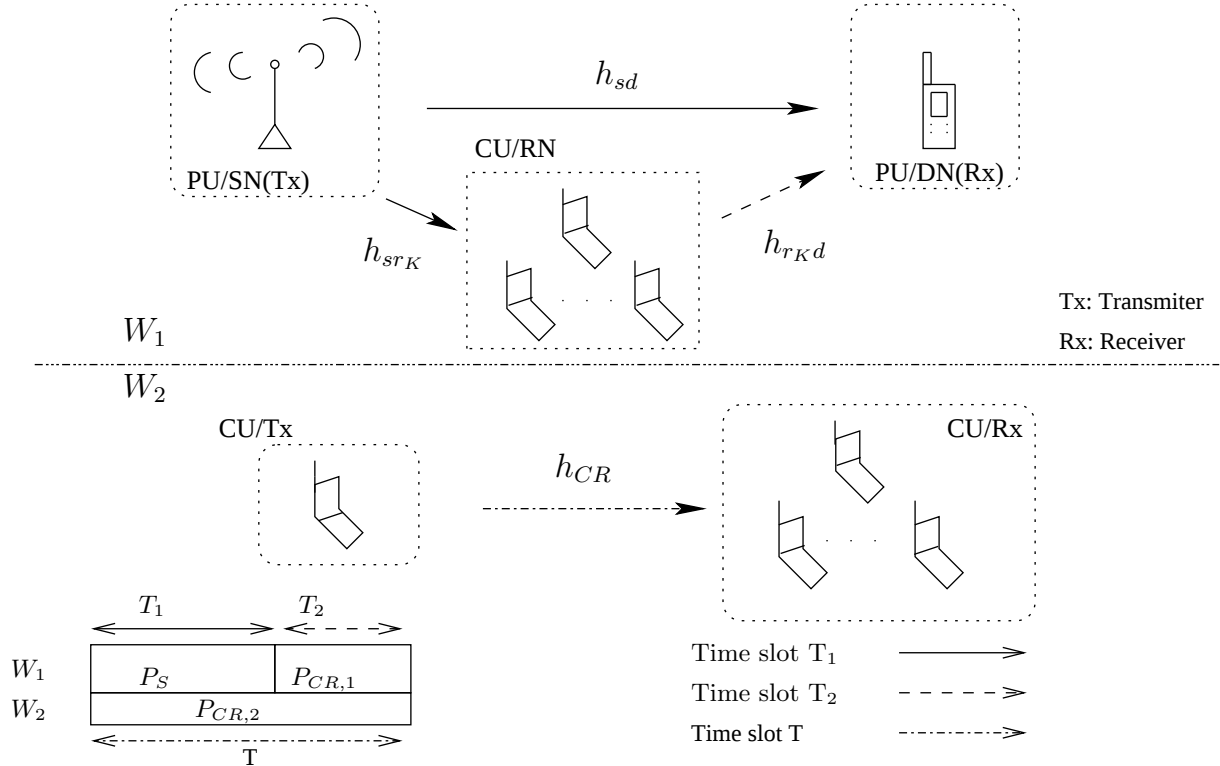


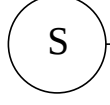
Fig. 1. The PU's and CU's spectrum-access model. The bandwidth, time period and power allocation for the PU and CU. The total time slot duration is $T = T_1 + T_2$ and the bandwidth is $W_0 = W_1 + W_2$

TTCM-8PSK: 2 bps

$\eta_A = 2$ bps

$\zeta_A = R_s^A$ sym/s

$\text{SNR}_t = 9$ dB



System A

$\text{BER} < 10^{-6}$

$R_b^A = 2R_s^A$ bit/s

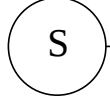
$\text{SNR}_r = 9$ dB

TTCM-64QAM: 5 bps

$\eta_B = 2.5$ bps

$\zeta_B = R_s^A$ sym/s

$\text{SNR}_t = 9$ dB



System B

$\text{BER} < 10^{-6}$

$R_b^B = 2.5R_s^A$ bit/s

$\text{SNR}_r = 18$ dB

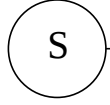
$\tilde{G} = 9$ dB

TTCM-64QAM: 5 bps

$\eta_C = 2.5$ bps

$\zeta_C = 0.8R_s^A$ sym/s

$\text{SNR}_t = 9$ dB



System C

$\text{BER} < 10^{-6}$

$R_b^C = 2R_s^A$ bit/s

$\text{SNR}_r = 18$ dB

$\tilde{G} = 9$ dB

Fig. 2. Comparison of a non-cooperative scheme and two relay-assisted DAF-CR schemes, where the target SNR_t is 9dB and the target BER is below 10^{-5} .

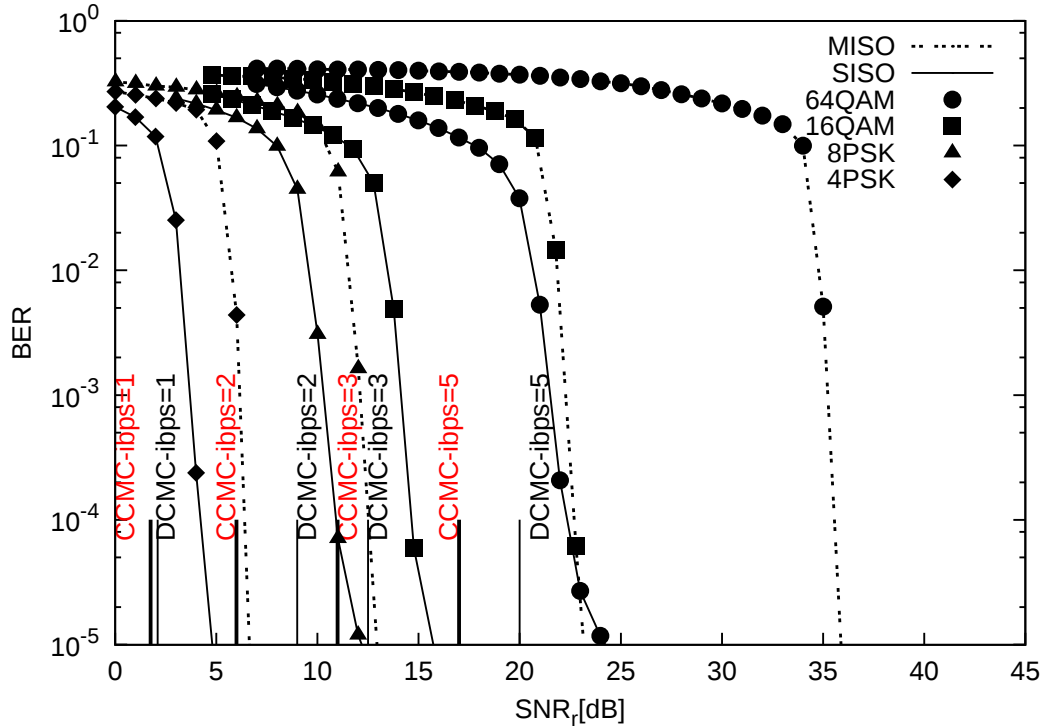


Fig. 3. The BER versus SNR_r performance of TTCM aided MISO system and TTCM aided SISO system. A frame length of 1200 symbols was employed when communicating over uncorrected Rayleigh channels. Four TTCM iterations and four outer iterations with the MISO detector is used in MISO system.

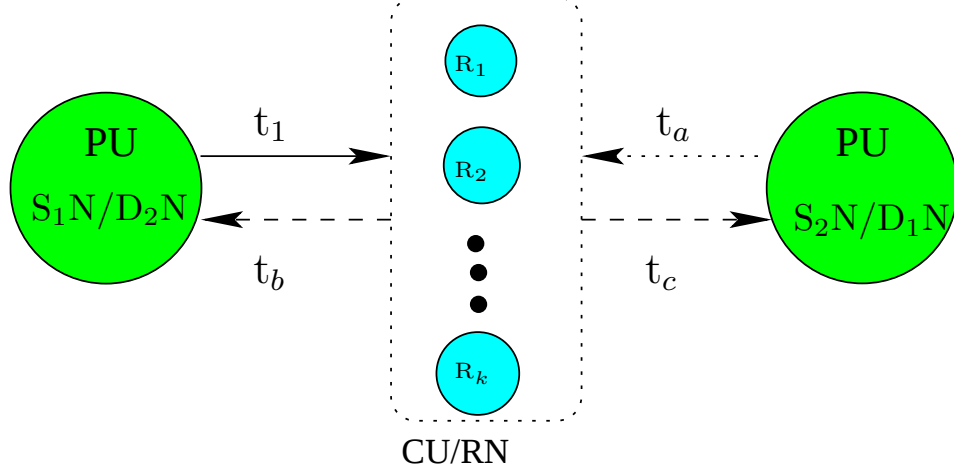


Fig. 4. The schematic of a two-way relay-aided system, including two PUs and K CUs. For MABC, $t_a = t_1$ and $t_b = t_c = t_2$, where t_1 is the first transmission period and t_2 is the second transmission period. For TDBC, $t_a = t_2$ and $t_b = t_c = t_3$, where t_3 is the third transmission period.

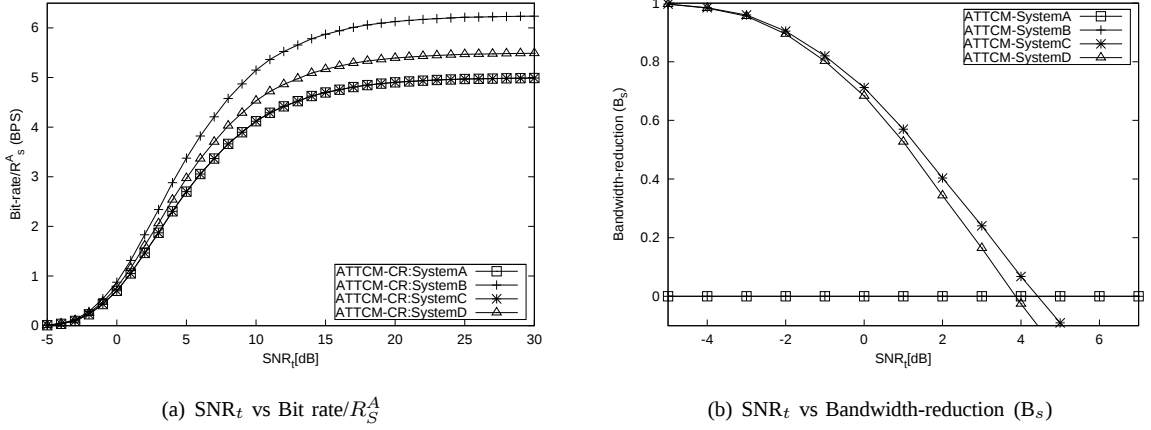
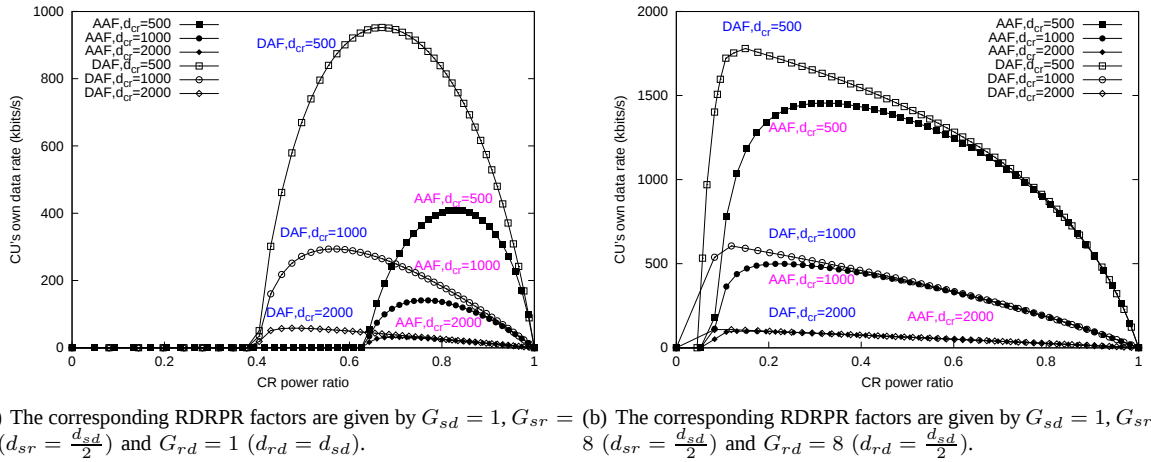


Fig. 5. Comparison of ATTCM aided System A, System B, System C and System D.



(a) The corresponding RDRPR factors are given by $G_{sd} = 1$, $G_{sr} = 8$ ($d_{sr} = \frac{d_{sd}}{2}$) and $G_{rd} = 1$ ($d_{rd} = d_{sd}$). (b) The corresponding RDRPR factors are given by $G_{sd} = 1$, $G_{sr} = 8$ ($d_{sr} = \frac{d_{sd}}{2}$) and $G_{rd} = 8$ ($d_{rd} = \frac{d_{sd}}{2}$).

Fig. 6. The CU's own data rate based on DAF and AAF detections.

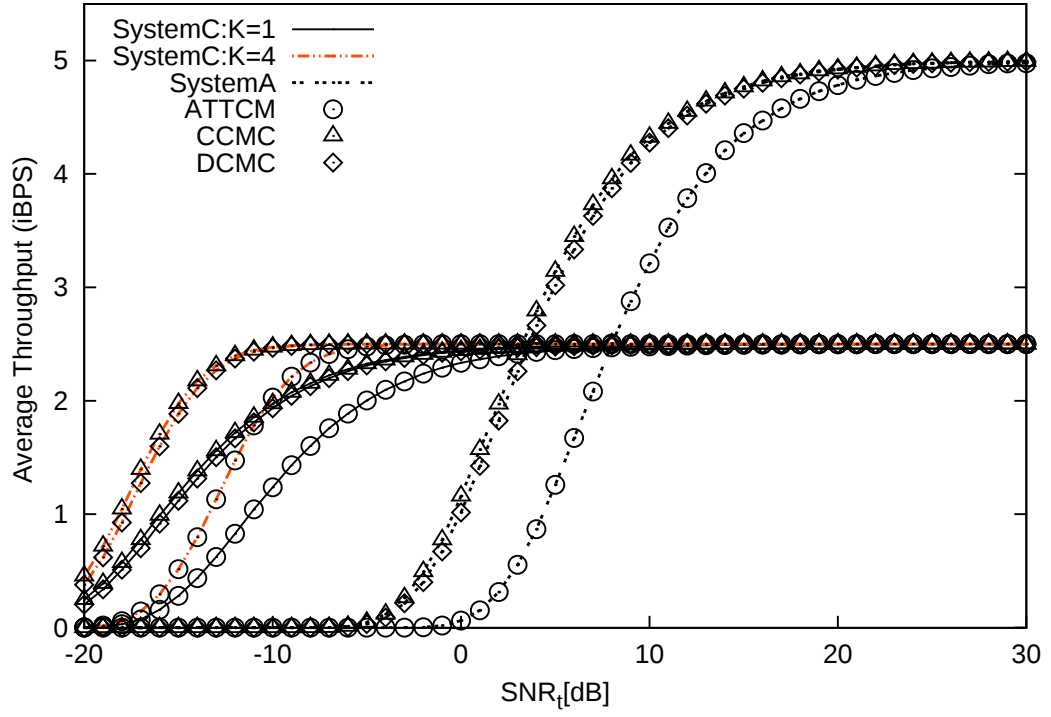


Fig. 7. iBPS versus SNR_t of the ATTTCM, CCMC and DCMC aided CR schemes when communicating over quasi-static Rayleigh fading channels. A BER below 10^{-5} is maintained and $G_{sr} = G_{rd} = 8$. The “SystemC” is represented by relay aided system of Section II-C.2, while the “SystemA” is refer to the non-cooperative System A of Section II-C.2. **The number of relays is $K = 1$ and $K = 4$.**

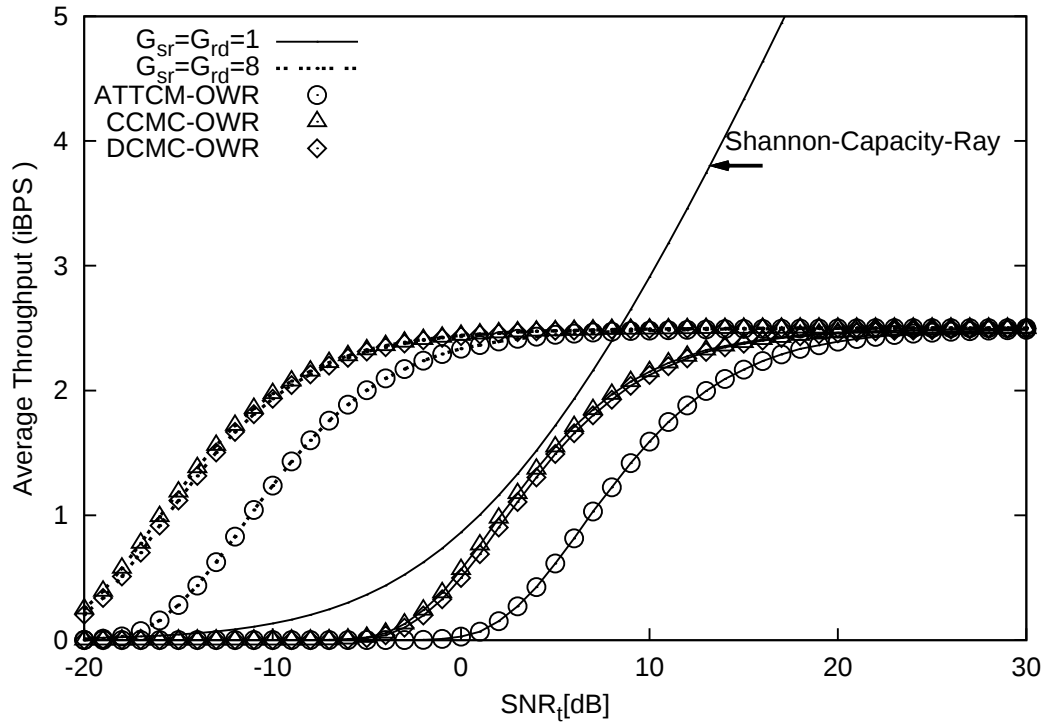


Fig. 8. iBPS versus SNR_t of the ATTTCM, CCMC and DCMC aided one-way relay in CR schemes when communicating over quasi-static Rayleigh fading channels compared to the CCMC capacity in Rayleigh channel. The “Shannon-Capacity-Ray” label refers to the CCMC capacity in Rayleigh channel. The number of relays is $K = 1$. The “OWR” is represented by one-way relay system. **The corresponding RDRPR are $G_{sr} = G_{rd} = 8$ and $G_{sr} = G_{rd} = 1$.**

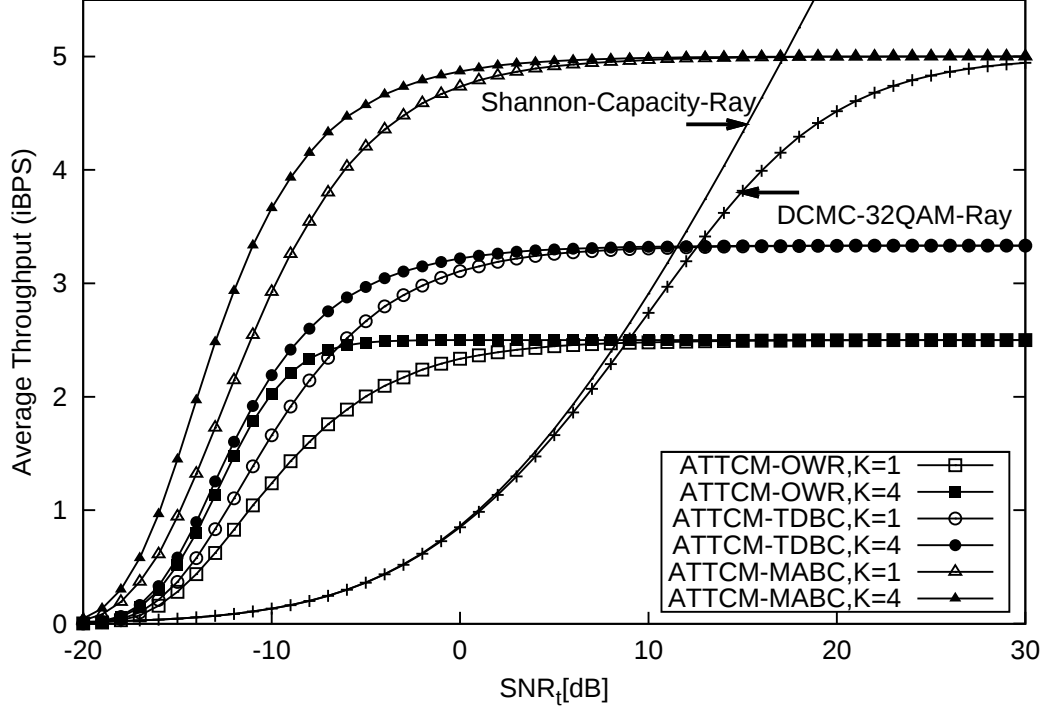


Fig. 9. iBPS versus SNR_t of the ATTCM aided one-way relay system and two-way relay system when communicating over quasi-static Rayleigh fading channels. The “DCMC-32QAM-Ray” refers to the DCMC capacity for 32QAM modulation in Rayleigh channel and the “Shannon-Capacity-Ray” refers to the CCMC capacity in Rayleigh channel. The “OWR” is represented by one-way relay system. **A BER below 10^{-5} is maintained and $G_{sr} = G_{rd} = 8$.**

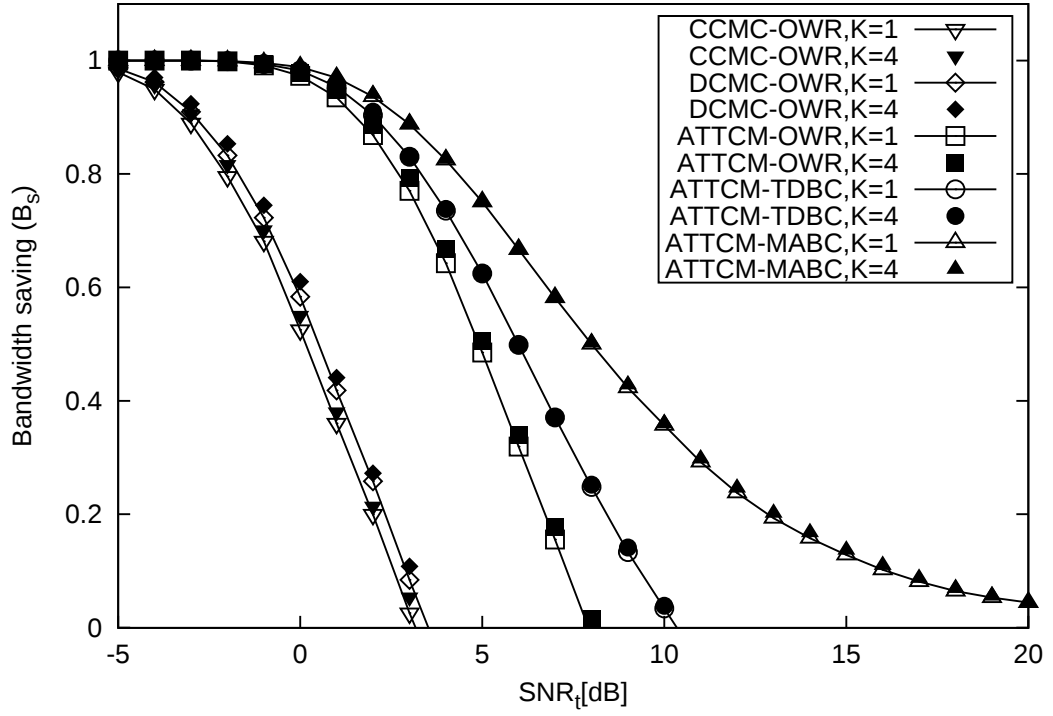


Fig. 10. Bandwidth reduction B_s versus SNR_t for ATTCM aided one-way relay and two-way relay CR schemes, when communicating over flat Rayleigh fading channels and maintaining a BER below 10^{-5} . The number of frames simulated was 1000. The “OWR” is represented by one-way relay system. $G_{sr} = G_{rd} = 8$, **The number of RNs in these schemes is $K = 1$ and $K = 4$.**