Network Coding Aided Cooperative Cognitive Radio for Uplink Transmission

Wei Liang, Hung Viet Nguyen, 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,hvn08r,sxn,lh}@ecs.soton.ac.uk, http://www-mobile.ecs.soton.ac.uk

***Abstract*— An uplink transmission for Adaptive Dynamic Network Coding (ADNC) assisted Cooperative Cognitive Radio (CCR) system is proposed for facilitating the recovery of the source information received from the Primary Users (PUs) at the BS. The Cognitive Users (CUs) acting as Relay Nodes invoke the ADNC technique, where the CCR-based control information is exchanged between the CUs and the BS. The network encoder may be activated in its adaptive mode for the sake of supporting the CUs, depending on the Boolean value of the feedback flags generated by the receiver based on the success/failure of the Adaptive Turbo Trellis Coded Modulation (ATTCM) channel decoder and of the network decoder. As a result, our novel ATTCM-ADNC-CCR system constructed based on a holistic approach is capable of providing an increased throughput, despite reducing the transmission-period of the PU. This reduced transmission-period can also be directly translated into an increased time-duration for the secondary communications of the CUs.**

***Index Terms*— Cognitive Radio network, Cooperative Communication, Adaptive Dynamic Network Coding, ATTCM.**

I. Introduction

The Cognitive Radio (CR) mechanism is capable of exploiting the temporarily available spectrum holes in the frequency domain. If a spectral-slot is not occupied by the Primary Users (PUs), then the Cognitive Users (CUs) (or secondary users) would have an opportunity to access it for their secondary communications based on the CR technique [1]. Spectrum sharing assisted cooperative communications has been widely investigated in the context of CR networks [2] Cooperative communications for spectrum sharing has been widely investigated in the CR networks [2]. Dynamic Network Codes (DNC) were proposed by Ming *et al.* in [3], where each user broadcasts his/her own information frames both to the Base Station (BS) as well as to the other users during the first transmission period. After this phase, each user transmits a non-binary linear combination of its own frame as well as of the other users' information frames to the BS [3]. The family of Generalized Dynamic Network Codes (GDNC) [4], [5] constitutes an extension of DNCs. In contrast to [3], the GDNC of [5] allows each user to broadcast several information frames during the broadcast phase via orthogonal channels [5], as well as to transmit several non-binary linear combinations, as parity frames during the cooperative phase via orthogonal channels. In order to increase the average transmission rate of GDNC without reducing its diversity order, an adaptive network code design was proposed in [4]. The design of network codes for multi-user, multi-relay scenarios has been investigated in [6], [7], where the users transmit their independent information to the BS with the aid of the RNs. In line with the system model proposed in [6], we assume that the CUs act as the RNs to help the PUs in transmitting their information to the BS. More specifically, in our proposed scheme, the CUs are capable of relaying the PU's message, while superimposing their own messages at the same time. This leads both to an increased overall throughput and to the reduction of the required transmission period of both the PUs and the CUs, thereby creating additional time-slots (TSs) for supporting additional users.

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Our contributions in [8] only considered simple RNs without the capability of invoking network coding. In this paper, the network coding schemes presented in [3]–[6] are incorporated into an active cooperation based overlay network conceived for a CR system. Additionally, we invoked Adaptive Dynamic Network Coding (ADNC) [4], where the CUs only deliver their information to the BS, if the BS failed to recover the source message from the PUs. Additionally, our proposed ADNC aided cooperative cognitive radio (CCR) scheme is intrinsically amalgamated with near-instantaneously adaptive coded modulation. Explicitly, we have opted for using bandwidth-efficient Turbo Trellis Coded Modulation (TTCM) [9], [10], because it was shown to outperform Trellis Coded Modulation (TCM), Bit-Interleaved Coded Modulation (BICM) and iteratively-decoded BICM [11]. The paper is organized as follows. Section II presents our system model and outlines the DNC scheme, the ATTCM scheme as well as the ADNC. Our novel ATTCM-ADNC-CCR arrangement is described in Section III. The performance of our proposed scheme is evaluated in Section IV. Finally, our conclusions are presented in Section V.

II. System Model

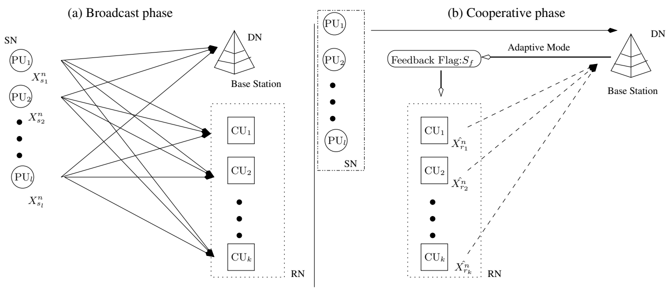

Fig. 1. The schematic of our proposed CCR scheme.

In our proposed system portrayed in Fig. 1, we consider the uplink (UL) transmission. We assume that each PU has a direct transmission link to the BS, as seen in Fig. 1. Additionally, we consider L PUs, where each PU broadcasts its information to a single BS and to K CUs during the broadcast phase. The BS then decodes the source information received from the PUs. Accordingly, the CUs encode the received information frames for constructing the corresponding parity frames, which are then transmitted to the BS during the cooperative phase. Hence the BSs receive the information frames from the PUs and also the parity frames from the CUs. We assume that our proposed scheme is a Time Division Multiple Access (TDMA) scheme, where the PUs do not transmit simultaneously for avoiding the inter-user interference.

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During the "(a) broadcast phase" seen in Fig. 1, the lth PU/SN broadcasts its information frame $X_{s_l}^n$ within the nth frame to both the CUs/RNs and to the BS. The signal received at the BS via the Source-to-Destination (SD) link is given by: $y_{s_l d}^n = \sqrt{G_{s_l d}}\sqrt{P_S} h_{s_l d} X_{s_l}^n + n$, while that received at the k CU/RN via the Source-to-Relay (SR) link is: $y_{s_l r_k}^n = \sqrt{G_{s_l r_k}}\sqrt{P_S} h_{s_l r_k} X_{s_l}^n + n$, where P_S is the transmission power per unit frequency emanating from the PU/SN and $n \in N$, where N is the total number of frames. The $(N \times L)$ PUs simultaneously broadcast $(N \times L)$ information frames during the time duration T_1. Since a network-coding aided DAF protocol is employed at each CU/RN, the kth RNs forward the decoded-and-reencoded information frame $\hat{X_{r_k}^n}$ during the nth frame to the BS. Then, during the "(b) cooperative phase" of Fig. 1, the signal received at the BS via the relay-to-destination (RD) link can be formulated as: $y_{r_k d}^n = \sqrt{G_{r_k d}}\sqrt{P_{CU}} h_{r_k d} \hat{X_{r_k}^n} + n$, where the CU/RN forwards the source information frame using the power P_{CU}. Similar to the broadcast phase, the overall transmissions during the cooperative phase are within the time duration of T_2.

In our proposed system, the CUs act as the RNs. Without loss of generality, we assumed that the RNs are located half-way between the PUs and BS. Similar performance trends would be observed if the RNs are located at random locations between the PUs and the BS. Accordingly, the Reduced-Distance-Related-Pathloss-Reduction (RDRPR) [12] experienced by the SR link is given by: $G_{sr} = (\frac{d_{sd}}{d_{sr}})^{\alpha}$, where α is the path-loss exponent [13]. Similarly, the RDRPR of the RD link with respect to the SD link is $G_{rd} = (\frac{d_{sd}}{d_{rd}})^{\alpha}$. Naturally, the RDRPR of the SD link with respect to itself is unity, i.e. we have $G_{s_l d} = 1$. We consider an outdoor environment [13], where $\alpha = 3$. Note that the same RDRPR is exploited by all the SR and RD links in our system. Thus, we have $G_{s_l r_k} = G_{r_k d} = 2^3 = 8$. Moreover, we consider a single non-dispersive transmission path for the SD, SR and RD links of our novel ATTCM-ADNC-CCR scheme. Each of the channels in our system is comprised of two components, which may be expressed as:

$$h = h_s \cdot h_f \; , \tag{1}$$

where the slow fading (or quasi static fading) coefficient h_s is constant for all symbols within a transmit frame. By contrast, the fast-fading (small-scale Rayleigh fading) coefficient h_f varies on a symbol by symbol basis, which will be described in Section II-A. The average received SNR at node b per frame is given by:

$$\begin{aligned} \gamma_R &= \frac{G_{ab} E[|x|^2] E[|h_f^2|] E[|h_s^2|]}{N_0} \; , \\ &= \frac{G_{ab} |h_{ab}|^2}{N_0} \; , \end{aligned} \tag{2}$$

where we have $E[|x|^2] = 1$ and $E[|h_f^2|] = 1$ for uncorrelated Rayleigh fading channels, which varies on a symbol by symbol basis, as discussed in Section II-A and we have $E[|h_s^2|] = |h_s|^2 = h_{ab}^2$.

A. Adaptive TTCM

ATTCM is advocated for judiciously selecting a suitable modulation mode according to the near-instantaneous channel condition experienced in each transmission link, which would lead to the reduction of the PU's transmission power and/or to the increase of the overall system throughput, hence simultaneously saving bandwidth for the CUs. In Fig. 2, both the PUs and CUs have employed ATTCM encoders, where the TTCM encoder comprises a pair of identical parallel-concatenated TCM encoders [14] linked by a symbol interleaver. Then the bit-to-symbol mapper maps the input bits to complex-valued ATTCM symbols using the classic Set Partition based labelling method [15]. Additionally, the BS decodes the information delivered from the PUs and CUs by the ATTCM decoder. The structure of the TTCM decoder is similar to that of binary turbo codes, where each decoder alternately processes its corresponding encoder's channel-impaired output symbol, and then the other encoder's channel-impaired output symbol [15, pg.764]. As shown in Fig. 2, we invoked a near-instantaneously adaptive TTCM scheme for protecting the SR and the RD links, where the effective throughput range is given by $R_{tran} = \{0, 1, 2, 3, 4, 5\}$ BPS when no transmission, QPSK, 8PSK, 16QAM, 32QAM and 64QAM are considered, respectively.

Moreover, the ATTCM mode switching thresholds Υ =$[\gamma_0, \gamma_1, \gamma_2, \gamma_3, \gamma_4]$ were determined based on the FER performance curves of each of the five TTCM schemes when communicating over a Rayleigh fading channel as shown in Fig. 3. We chose the switching thresholds carefully to ensure that the FER at the RN is lower than 10^{-3}, in order to minimize the potential error propagation from the CUs to the BS, which are given by Υ_{ATTCM}=[5.22, 12.25, 16.10, 21.15, 24.49] dB. Specifically, both the ATTCM mode

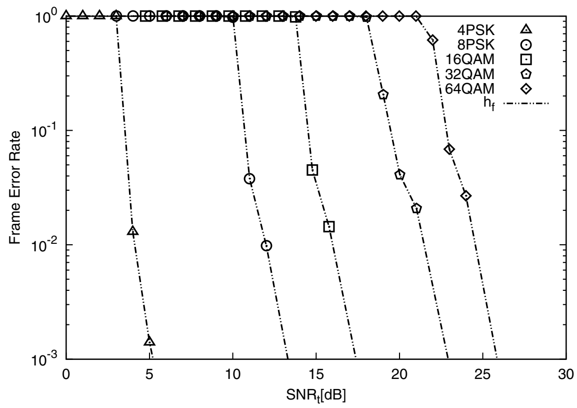

Fig. 3. The FER performance versus SNR_t of TTCM a frame length of 12,000 symbols, when communicating over Rayleigh fading channels. Four TTCM iterations were invoked.

switching operation and the transmission rate of the modes are based on the following algorithm:

$$\text{MODE} = \begin{cases} \gamma_4 \le \gamma_R, & \text{TTCM-64QAM, } C^*\text{=5 ibps;} \\ \gamma_3 \le \gamma_R < \gamma_4, & \text{TTCM-32QAM, } C^*\text{=4 ibps;} \\ \gamma_2 \le \gamma_R < \gamma_3, & \text{TTCM-16QAM, } C^*\text{=3 ibps;} \\ \gamma_1 \le \gamma_R < \gamma_2, & \text{TTCM-8PSK, } C^*\text{=2 ibps;} \\ \gamma_0 \le \gamma_R < \gamma_1, & \text{TTCM-4PSK, } C^*\text{=1 ibps;} \\ \gamma_R < \gamma_0, & \text{No transmission, } C^*\text{=0 ibps;} \end{cases} \tag{3}$$

where C^* is the effective throughput in terms of the number of information bit per symbol (ibps).

B. Network Encoder and Decoder

This section is devoted to detailing the encoding/decoding process of the network coding technique. As an illustration, we present a specific example associated with $L = 4$ PUs and $K = 4$ CUs, where we have orthogonal channels among the pairs of PUs and CUs. The coding arrangement of this specific example can be summarized as

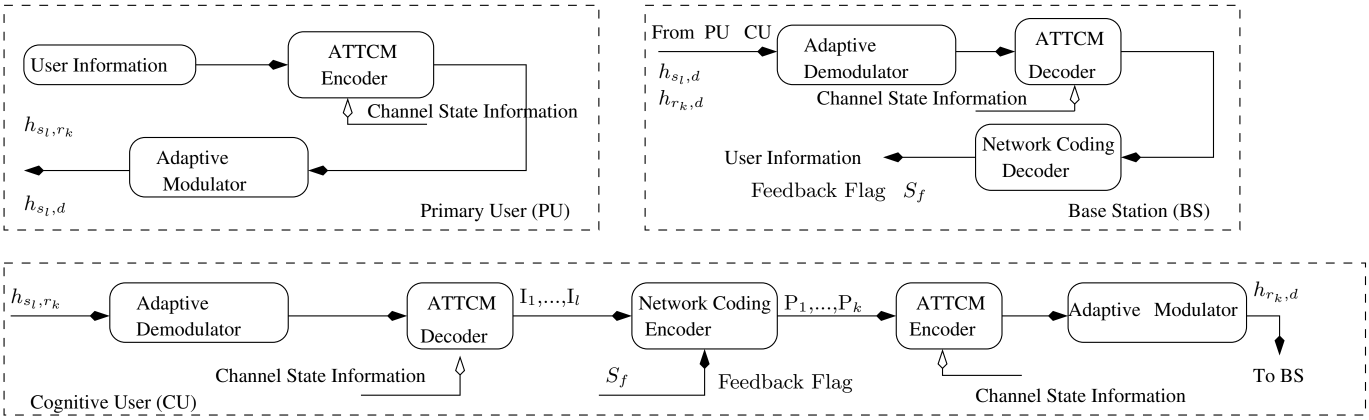

Fig. 2. The architecture in SNs, RNs and BS of our ATTCM-ADNC-CCR scheme.

follows:

$$(BP_1) : PU_1 \xrightarrow[(=0/1)]{I_1} CU_1/CU_2/CU_3/CU_4,\ PU_1 \xrightarrow[(=0/1)]{I_1} BS\ ;$$

$$(BP_2) : PU_2 \xrightarrow[(=0/1)]{I_2} CU_1/CU_2/CU_3/CU_4,\ PU_2 \xrightarrow[(=0/1)]{I_2} BS\ ;$$

$$(BP_3) : PU_3 \xrightarrow[(=0/1)]{I_3} CU_1/CU_2/CU_3/CU_4,\ PU_3 \xrightarrow[(=0/1)]{I_3} BS\ ;$$

$$(BP_4) : PU_4 \xrightarrow[(=0/1)]{I_4} CU_1/CU_2/CU_3/CU_4,\ PU_4 \xrightarrow[(=0/1)]{I_4} BS\ ;$$

$$(CP_1) : CU_1 \xrightarrow[(=0/1)]{M_{4\times 8}(1,5)\cdot I_1 \oplus M_{4\times 8}(2,5)\cdot I_2 \oplus M_{4\times 8}(3,5)\cdot I_3 \oplus M_{4\times 8}(4,5)\cdot I_4} BS\ ;$$

$$(CP_2) : CU_2 \xrightarrow[(=0/1)]{M_{4\times 8}(1,6)\cdot I_1 \oplus M_{4\times 8}(2,6)\cdot I_2 \oplus M_{4\times 8}(3,6)\cdot I_3 \oplus M_{4\times 8}(4,6)\cdot I_4} BS\ ;$$

$$(CP_3) : CU_1 \xrightarrow[(=0/1)]{M_{4\times 8}(1,7)\cdot I_1 \oplus M_{4\times 8}(2,7)\cdot I_2 \oplus M_{4\times 8}(3,7)\cdot I_3 \oplus M_{4\times 8}(4,7)\cdot I_4} BS\ ;$$

$$(CP_4) : CU_2 \xrightarrow[(=0/1)]{M_{4\times 8}(1,8)\cdot I_1 \oplus M_{4\times 8}(2,8)\cdot I_2 \oplus M_{4\times 8}(3,8)\cdot I_3 \oplus M_{4\times 8}(4,8)\cdot I_4} BS\ .$$

Note that the arrow '→ ' represents the transmission direction. The notation $0/1$ below the right arrow of the above arrangement indicates whether the transmission was successful or not, where I_l is defined in Eq. (6). The notation '⊕' represents the non-binary linear combination of the information frames. The corresponding transfer matrix $M_{4\times 8}$ of [4], [5] constructed for our specific system is defined as:

$$M_{4\times 8} = \begin{bmatrix} 1 & 0 & 0 & 0 & | & 3 & 7 & 3 & 6 \\ 0 & 1 & 0 & 0 & | & 5 & 7 & 7 & 4 \\ 0 & 0 & 1 & 0 & | & 2 & 4 & 6 & 1 \\ 0 & 0 & 0 & 1 & | & 5 & 5 & 3 & 2 \end{bmatrix} . \tag{4}$$

We also define the modified transfer matrix $M'_{4\times 8}$ with respect to the original transfer matrix $M_{4\times 8}$, which takes into account the success/failure of each transmission during a specific transmission session. In order to detect the information frames of the PUs, the BS has to be aware of how each parity frame was constructed at the CUs. Hence the modified transfer matrix $M'_{i\times j}$ is assumed to be known at the BS. If all the transmitted frames are successfully decoded, the modified transfer matrix is defined as $M'_{4\times 8}(i,j) = M_{4\times 8}(i,j)$.

The output codewords of the CUs are denoted as: $\{\overleftrightarrow{\hat{X}^n_{r_k}}\}^K_{k=1}$, while those of the kth CU during the nth frame may be expressed as:

$$\hat{X}^n_{r_k} = M \cdot X^n_{s_l} = [\hat{I}_l \mid \hat{P}_k]\ , \tag{5}$$

where $X^n_{s_l}$ is the information frame transmitted from the lth PU within the nth frame to both the CUs and to the BS. Additionally, the transfer matrix M defined in [3] describes the corresponding network codes invoked for our DNC-CCR scheme. As seen in Fig. 4, the transfer matrix M is comprised of two components, since we have $M = [I_l|P_k]$, where the identity matrix $\{I\}_l$ $(l \in L)$, represents the sequences transmitted from the PUs during the broadcast phase, while the parity matrix $\{P\}_{l\times k}$ $(k \in K)$ represents to the CUs' transmissions during the cooperative phase. Therefore, the corresponding entry I_l in Fig. 4 represents the successful/unsuccessful reception of the information frame recovered at the BS during the broadcast phase, which obeys the following rule:

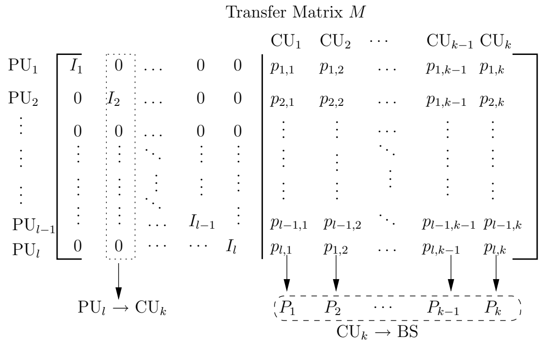

Fig. 4. Illustration of the transfer matrix of the DNC-CCR scheme.

$$I_l = \begin{cases} 0, & \text{If } X^n_{s_1} \text{ is not recovered successfully at the BS;} \\ 1, & \text{If } X^n_{s_1} \text{ is recovered successfully at the BS;} \end{cases} \tag{6}$$

We note that the coefficient $p_{l,k}$ shown in Fig. 4 is gleaned from the transfer matrix of a linear block code defined over the Galois field $GF(|q|)$, where $|q|$ is the alphabet size ($q = 2^b$), and b is an integer higher than zero [4], [6]. The transfer matrix constructed over the $GF(|q|)$ is provided by the software application SAGE [16]. As shown in Fig. 4, the variable $p_{l,k}$ represents the specific transmission state, during which the information frame is transmitted from PU_l to CU_k as detailed below:

$$p_{l,k} = \begin{cases} 0, & \text{unsuccessful;} \\ 1, & \text{successful;} \end{cases} \tag{7}$$

The network encoding process is represented by Eq (5), where we construct the parity frames $\hat{P}_k = [P_1, P_2, \ldots, P_{k-1}, P_k]$ from the K CUs. Additionally, the parity frame transmitted by the kth CU is given by: $P_k = I_1 p_{1,k} \oplus I_2 p_{2,k} \oplus \cdots \oplus I_l p_{l,k}$.

C. Principle of Adaptive Dynamic Network Coding

In our ADNC scheme, we assume that the network-coding decoder at the BS is capable of sending back a feedback flag to the network encoders at the CU/RNs, as shown in Fig. 1. The transmission of the parity frames from the CUs is controlled by this feedback flag. By referring to [4], the ADNC adaptively adjusts the number of frames transmitted from the CUs for each transmission session. The BS feeds back a single bit, S_f, following the reception of a set of $(L \times m_1)$ information frames from the L PUs, where m_1 denotes the number of information frame transmitted per PU. If the CU/RNs received $S_f = 0$, this implies that the BS has failed to correctly decode the information frames received from all the PU/SNs and hence the CU/RNs have to transmit $(K \times m_2)$ parity frames to the BS, which m_2 denotes the number of information frame transmitted per CU. Otherwise, if the BS successfully decoded the PU's information, the value of the feedback flag is set to $S_f = 1$. Let us denote the number of CUs invoked in an actual transmission by employing the ADNC technique during the cooperative phase as $K^{'}$. The actual number of information frames, $K^{'} m_2$, transmitted from the K CUs by the ADNC-M1 technique obeys the following rules:

$$K^{'} m_2 = \begin{cases} 0, & S_f\text{=1;} \\ K m_2, & S_f\text{=0;} \end{cases} \tag{8}$$

More specifically, if the BS only successfully received some of the information frames from the PUs, it will send a feedback flag of $S_f = 0$ to the CUs, which will trigger a retransmission of all the information frames from the RNs to the BS. In our system, the BS feeds back a small amount of information to the CUs, which may impose an overhead. However, unnecessary retransmission can be avoided, when a feedback of $S_f = 1$ was received by the RNs.

III. System Design

In this section, the design guidelines of our proposed system will be discussed first. Then the transmission rates of ADNC of our proposed system is analysed.

A. Adaptive TTCM transmission scenario

All transmission links shown in Fig. 1 have employed the ATTCM scheme detailed in Eq. (3), where each link may employ different modulation modes during the entire transmission period. Under the DNC policy of Section II-B, the PUs transmit at the same rate during the broadcast phase. We consider the "worst" PU, whose link towards both the CUs and the BS has the lowest SNR, which forces some of the PUs which actually experience a high SNR to transmit at a rate lower than their own affordable rate. This allows the CU to perform bit-by-bit combination of the decoded information. Thus, the lowest-rate, but most resilient modulation modes are activated for all the L SD and L SR links, which also affects the $(L \times K)$ SR links. The rate achievable at the SNs of our proposed scheme during the broadcast phases can be written as:

$$R_{Tx}^{PU_l} \quad = \quad \min\{C_{s_l d}^{*}, C_{s_l r_k}^{*}\}, \quad l \in L \ , k \in K \ . \tag{9}$$

As for the K RD links, each link obeys the adaptive modulation mode selection rule of Eq. (3). Additionally, the achievable rate of the CU/RN to BS link during the cooperative phases is given by:

$$R_{Tx}^{CU_k} \quad = \quad \max\{C_{r_k d}^{*}\}, \quad k \in K \ , \tag{10}$$

where the values of $C_{s_l d}^{*}$, $C_{s_l r_k}^{*}$ and $C_{r_k d}^{*}$ can be obtained from Eq. (3), depending on the instantaneous channel conditions. Therefore, the CUs transmit the same information which is the highest rate among all the RD links during the cooperative phase. The transmission in the broadcast and cooperative phases may be represented by the transfer matrix, as shown in Fig. 4.

B. Analysis of Transmission Rate

In this section, we investigate the attainable transmission rate of our proposed scheme. We assume that we have N-frame sessions and the length of each time-slot (TS) in the frame is T. As discussed in Section II, this TS is split into two parts, yielding $T = T_1 + T_2$, where T_1 is used for the PU's transmission during the broadcast phase and T_2 is allocated for the CUs to relay the combined information of both the PU and CU during the cooperative phase. If the PU activates a higher-throughput modulation mode, then the SNR required by the PU will be high. As a benefit, this will shorten the PU's transmission duration of T_1. Consequently, this would grant a longer transmission period for the CUs. Thus, we increase T_2, when T_1 is reduced. Moreover, we assumed that the PU and CU have the same Baud-rate (symbol rate) of $R_s^{PU} = R_s^{CU}$ symbol/s during the entire transmission period. Meanwhile, the number of bits transmitted by the PU and CU in a single transmission session is the same, namely $N_b^{PU} = N_b^{CU}$ bits. Then the number of bits transmitted during the broadcast phase is given by:

$$N_b^{PU} = L \ R_s^{PU} \ R_{Tx}^{PU_l} \ T_1 \ , \tag{11}$$

while those during the cooperative phase is:

$$N_b^{CU} = K^{'} \ R_s^{CU} \ R_{Tx}^{CU_k} \ T_2 \ , \tag{12}$$

where $K^{'}$ was defined in Section II-C. Then the Baud rate of the PU is $R_s^{PU} = N_b^{PU}/T_1$, while that of the CU is $R_s^{CU} = N_b^{CU}/T_2$. In our proposed system, the TSs are shared by the PU and CU. We assumed that the amount of information to be transmitted by the PU and CU is identical, thus we have:

$$L \ R_s^{PU} \ R_{Tx}^{PU_l} \ T_1 = K^{'} \ R_s^{CU} \ R_{Tx}^{CU_k} \ T_2 \ . \tag{13}$$

Then, based on Eq. (13), the relationship between T_1 and T_2 is given by:

$$\frac{T_2}{T_1} \quad = \quad \frac{L \ R_s^{PU} \ R_{Tx}^{PU_l}}{K' \ R_s^{CU} \ R_{Tx}^{CU_k}} \ . \tag{14}$$

Since $T_2 = T - T_1$, based on Eq. (14), we have

$$T_1 \quad = \quad \frac{K^{'} \ R_{Tx}^{CU_k}}{L \ R_{Tx}^{PU_l} + K' \ R_{Tx}^{CU_k}} \ T \ . \tag{15}$$

The average throughput of the entire system may be quantified by the ratio of the total number of transmitted information bits divided by the number of transmission TSs. This metric is similar to the concept of the overall rate defined in [7, (18)]. We also assume that our proposed system transmits its messages at the same rate during each N-frame session. Let us now consider the achievable transmission rate of our proposed ADNC-CCR scheme. If all the PUs transmit all their messages to the BS successfully, the CUs do not have to relay the source information to the BSs. By contrast, the CUs will relay the source information to the BS, if the transmissions from the PU to the BS failed. Thus we can obtain the time allocations between PUs and CUs as follows:

$$T_1 \begin{cases} = T, \ T_2 = 0; \ \text{If the PU's transmission is successful.} \\ = \frac{K^{'} \ R_{Tx}^{CU_k}}{L \ R_{Tx}^{PU_l} + K^{'} \ R_{Tx}^{CU_k}} \ T, \ T_2 = T - T_1; \ \text{Otherwise;} \end{cases}$$

Moreover, if the PU transmitted successfully to the BS, we can save the entire T_2 duration for the CU's communication. However, if the PU failed to successfully transmit its message to the BS, then the CU would relay the PU's message to the BS. If the transmit SNR of the PU is higher, the relaying period of the CU will be reduced and this allows the system to grant a longer transmit-duration for the CUs. By contrast, at a low SNR the opposite trend prevails. Hence, the overall throughput per frame per user of the proposed ADNC scheme is given by:

$$\eta_{ADNC} = \begin{cases} \frac{1}{N} \sum_{n=1}^{N} \frac{\sum_{l=1}^{L} R_{Tx}^{PU_l}}{L} & \text{PU's transmission was successful;} \\ \frac{1}{N} \sum_{n=1}^{N} \frac{\sum_{l=1}^{L} R_{Tx}^{PU_l} T_1}{L \times T} & \text{PU's transmission failed;} \end{cases} \tag{16}$$

where T_1 is defined in Eq. (15). Furthermore, the overall transmission rate per frame per user of the non-cooperative scheme recorded for the whole TS duration T becomes: $\eta_{SD} = \frac{1}{N}\sum_{n=1}^{N} \frac{\sum_{l=1}^{L} R_{Tx}^{PU_l}}{L}$. Finally, the overall performance of our system are shown in Section IV.

IV. Numerical Results and Discussions

TABLE I
THE MAIN PARAMETERS OF OUR PROPOSED SYSTEM.

Channel	Rayleigh and Quasi static fading channel
Number of frames N	10^6
Coding/Modulation	ATTCM
Modulation	Q-PSK, 8-PSK, 16-QAM, 32-QAM, 64-QAM
FER bound	10^{-3}
Transfer matrix of DNC	$M_{2\times4}$, $M_{4\times8}$
Number of PUs	$L = 2, 4$
Number of CUs	$K = 2, 4$
m_1 [frame]	1
m_2 [frame]	1
Pathloss exponent α	3

Fig. 5 shows the FER versus *transmit SNR*[1] SNR_t performance of $M_{2\times4}$ and $M_{4\times8}$-based System employing the ADNC arrangement, which the parameters are shown in Table I when transmitting over our combined[2] quasi-static (shadow) and Rayleigh (fast) fading channels. Additionally the corresponding transfer matrix of $M_{2\times4}$ scheme [4], [5] is

$$M_{2\times4} = \begin{bmatrix} 1 & 0 & | & 1 & 1 \\ 0 & 1 & | & 1 & 2 \end{bmatrix} . \quad (17)$$

In Fig. 5, we compare the throughput of three schemes at a comparable FER. Explicitly, the non-cooperative scheme employed the BPSK, 8PSK, 16QAM of ATTCM transmission modes. The reason for considering three modulation modes for our non-cooperative scheme is because the FER performance of the non-cooperative benchmark scheme is somewhat poor. If a 32QAM modulation mode were to be used, the FER would become excessive. Hence we opted for four modulation modes for our ATTCM-ADNC-CCR $M_{2\times4}$ matrix. Observe in Fig. 5 that the FER recorded at the RN becomes lower than 10^{-3} both for the ADNC and for the non-cooperative scheme. The FER performance curves of the $M_{2\times4}$ and of the $M_{4\times8}$-based ATTCM-ADNC-CCR scheme and of the non-cooperative scheme crossed each other at $SNR_t = 7$ dB. Beyond that point, the FER performance of the ADNC scheme became better than that of the non-cooperative scheme, namely for $\text{SNR}_t > 12$ dB. Moreover, at FER=10^{-4} our proposed $M_{4\times8}$-based scheme attains an 30 dB -22 dB$= 8$ dB gain compared to the non-cooperative scheme.

As observed in Fig. 5, our proposed $M_{4\times8}$-based ADNC scheme has a better throughput than the non-cooperative scheme for $SNR_t >$ 28 dB. Explicitly, we found in Fig. 5 that the ADNC scheme achieved a throughput of 5.0 bps, which is $5.0 - 3.0 = 2.0$ bits higher than that of the non-cooperative scheme at $\text{SNR}_t = 45$ dB. Observe furthermore in Fig. 5 that the throughput of the $M_{2\times4}$-based ADNC scheme is higher than that of the non-cooperative scheme for $SNR_t > 20$ dB. More specifically, the proposed $M_{4\times8}$-based ADNC scheme requires four TSs, while the $M_{2\times4}$-based scheme only requires two TSs, when the BS failed to flawlessly receive the source information from the SN, albeit these ADNC schemes failed to achieve a higher throughput for low SNR_t. Hence, it is better to activate a non-cooperative model at a low SNR, since its throughput per user per link is better. Then the "SNR-adaptive" ATTCM-ADNC-CCR system characterized in Fig. 5 is the scheme that always activates the best scheme for the set of non-cooperative $M_{2\times4}$- and $M_{4\times8}$- based systems in terms of the average throughput as a function of the SNR. Note that at FER=10^{-4} the FER performance of the "SNR-adaptive" scheme is better than that of the $M_{2\times4}$-based arrangement, but at FER=10^{-5} worse than that of the $M_{4\times8}$ based scheme.

The bandwidth-reduction factor (B_s) may be formulated as [8]:

$$B_s = 1 - \frac{\eta_{SD}}{\eta_{ADNC}} , \quad (18)$$

where η_{SD} and η_{ADNC} are defined in Section III-B. In Fig. 6, we consider the attainable bandwidth reduction versus SNR_t for our ATTCM-ADNC-CCR system based on the $M_{2\times4}$ and $M_{4\times8}$ matrices of Table I. It is observed in Fig. 6 that the highest bandwidth reduction is achieved by the $M_{4\times8}$-based ADNC scheme, which

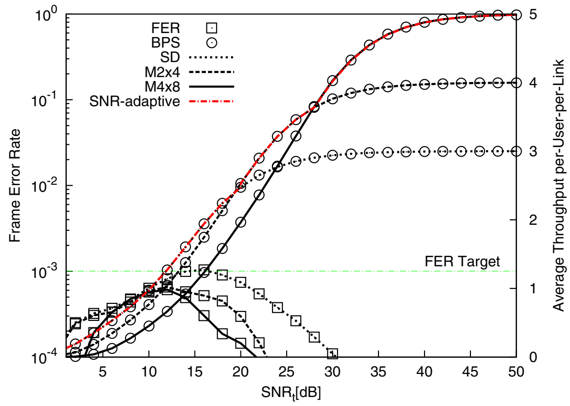

Fig. 5. The FER performance and average throughput per user per link versus SNR_t of the proposed ATTCM-ADNC-CCR scheme. "SD", "M2x4" and "M4x8" represents the FER and average throughput of our ATTCM aided non-cooperative scheme using one of three modulation modes and the ADNC scheme for four and five modulation modes based on matrix $M_{2\times4}$ and $M_{4\times8}$, respectively. "SNR-adaptive" ATTCM-ADNC-CCR scheme is represented that always activates the best scheme for the set of "SD", "M2x4" and "M4x8" based schemes in terms of the average throughput as a function of the SNR which has described in Section IV.

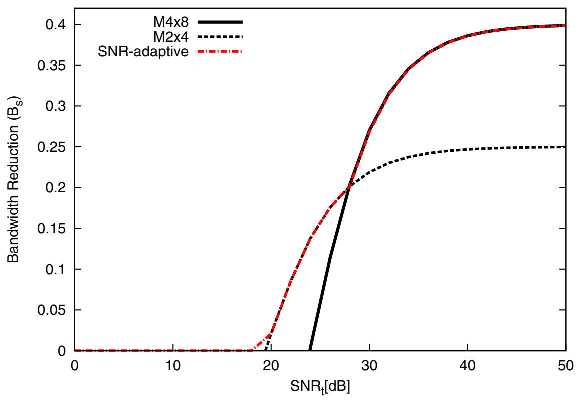

Fig. 6. The bandwidth reduction B_s versus SNR_t of the proposed ATTCM-ADNC-CCR scheme. "SD", "M2x4" and "M4x8" are denoted the FER and average throughput of ATTCM aided non-cooperative scheme using one of three modulation modes and the ADNC scheme for four and five modulation modes based on matrix $M_{2\times4}$ and $M_{4\times8}$, respectively. "SNR-adaptive" ATTCM-ADNC-CCR scheme is represented that always activates the best scheme for the set of "SD", "M2x4" and "M4x8" based schemes in terms of the average throughput as a function of the SNR which has described in Section IV.

[1] The concept of transmit SNR [12] 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. However, this is a computationally convenient definition.

[2] When the channel gain incorporates both the shadow- and fast-fading components, the adaptive transmission regime counteracts the shadow fading, but it is typically unable to accommodate the Rayleigh-fading.

results in $B_s = 40\%$ for $SNR_t \geq 43$ dB. Observe in Fig. 5 that the corresponding maximum throughput of the ADNC scheme is $\eta_{ADNC} = 5$, while that of the non-cooperative scheme is $\eta_{SD} = 3$. Thus, based on Eq. (18), we arrive at $B_s = 1 - \frac{3}{5} = 0.4 = 40\%$. By referring to Fig. 6, we observe that the $M_{2\times4}$-based scheme may achieve $B_s = 25\%$ at high SNRs, namely for $SNR_t \geq 32$ dB. Thus, the $M_{4\times8}$-based ADNC scheme is capable of saving (40% -25%)= 15% more bandwidth than the $M_{2\times4}$-based ADNC scheme. Moreover, the performance of the "SNR-adaptive" ATTCM-ADNC-CCR scheme characterized in Fig. 6 provides the highest bandwidth for the PU, regardless of the SNR.

V. Conclusions

An uplink transmission for ATTCM aided ADNC assisted CCR scheme was conceived, where both the ATTCM modulation mode and the ADNC technique were configured according to the near-instantaneous channel conditions. We found that the proposed ADNC aided CCR scheme could be used for releasing up to 40% of bandwidth for exploitation by the CUs.

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