2012 IEEE Wireless Communications and Networking Conference: Mobile and Wireless Networks

Adaptive Turbo Trellis Coded Modulation Aided Cooperative Cognitive Radio

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— **An adaptive Turbo Trellis Coded Modulation (ATTCM) aided Cognitive Radio (CR) scheme is proposed for cooperative communication among Primary Users (PUs) and Cognitive Users (CUs). The new 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). More specifically, an active cooperation between the PU and the CU would lead to a reduction of the transmission power and/or to an increased transmission rate for the PU. These benefits may be translated into a reduced transmission bandwidth and the freed bandwidth may be leased to a group of CUs for their secondary communications. Furthermore, our ATTCM scheme appropriately adjusts the code rate and the modulation mode according to the near-instantaneous channel conditions. The ATTCM switching thresholds are chosen to ensure that the Bit Error Ratio (BER) is below 10^{-6} 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 CR techniques may lead to significant mutual benefits for both the PUs and the CUs.**

Index Terms— **Adaptive Turbo Trellis Coded Modulation (ATTCM), Cognitive Radio network, Cooperative Communication.**

I. INTRODUCTION

Cognitive Radio (CR) is an emerging technology that enables the flexible development, construction, production, shipping and deployment of highly adaptive radios that are conceived on the basis of software defined radio technology [1]. They are 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 secondary communication 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].

Cooperative communication systems, rely on three types of nodes, namely the Source Node (SN), the Relay Node (RN) and the Destination Node (DN). The two most popular collaborative protocols used between the source, relay and destination nodes are the Decode-And-Forward (DAF) and the Amplify-And-Forward (AAF) schemes [4]. 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 [5]. More specifically, the first type is similar to the traditional cooperative communication. In the third type, a CU may act as a RN for other CUs, which may have different available spectra [5]. For the second type, the PUs have a higher priority than the CUs, where the CUs may act as RN for PUs [6]. More specifically, the active cooperation [6] among the PUs and CUs would allow the PUs to transmit at a lower power and/or a higher throughput, while at the same time enabling the CUs to communicate using the released bandwidth. Another interesting protocol involving simultaneous transmissions of the PUs and CUs has been proposed in [3] for maximizing the overall achievable rate. In this contribution, we consider the actual coding and modulation schemes in the context of an active cooperation based CR system.

Turbo Trellis Coded Modulation (TTCM) [7], [8] is a joint coding and modulation scheme that has a structure similar to binary turbo codes, where two identical parallel-concatenated Trellis Coded Modulation (TCM) schemes are employed as component codes. In our work, we consider an Adaptive TTCM (ATTCM) aided cooperative CR scheme, which relies on cooperation of the source PU and the destination PU with the aid of the CUs acting as RNs. The transmission rate/throughput of the 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. Furthermore, we have also considered idealistic adaptive schemes based on both the Continuous-input Continuous-output Memoryless Channel (CCMC) and the Discrete-input Continuous-output Memoryless Channel (DCMC) [9]. More specifically, the CCMC based adaptive scheme assumes that idealistic 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 to operate right at the modulation-dependent DCMC capacity. Moreover, in order to render the active cooperation [6] between the PUs and the CUs to be more realistic, we have also considered the reduced-distance-related-pathloss-reduction for each transmission link.

The paper is organized as follows. The system design of the idealistic cooperative CR scheme capable of operating at Shannon's capacity is outlined in Section II-A. Our novel and realistic ATTCM-aided cooperative CR scheme is described in Section II-B. The performance of our proposed schemes is evaluated in Section III. Finally, our conclusions are presented in Section IV.

II. SYSTEM MODEL

A. System Design of Idealistic Cooperative Cognitive Radio Scheme

In this section, we follow [6] to consider a cooperative CR scheme involving the cooperation between a PU (as the SN) and a CU (as the RN) to convey the source message to another PU (as the DN).

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/SN 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 SN and DN will share the bandwidth W_1 to convey the source message to the PU/DN, 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

The financial support of the EPSRC UK under the China-UK science bridge and the India-UK Advanced Technology centre, as well as that of the European Union under the auspices of the Optimix project is gratefully acknowledged.

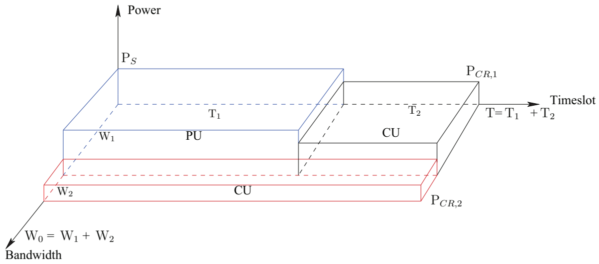

Fig. 1. The bandwidth, time period and power allocation for the PU and CU. The total time slot duration is $T = T_1 + T_2$ and the bandwidth is $W_0 = W_1 + W_2$.

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 PU/DN and the CU/RN. The signal received at the PU/DN via the Source-to-Destination (SD) link is given by:

$$Y_{sd} = \sqrt{P_S} h_{sd} X + n_{sd} \ , \tag{1}$$

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

$$Y_{sr} = \sqrt{P_S} h_{sr} X + n_{sr} \ , \tag{2}$$

where n_{sd} and n_{sr} are the Additive White Gaussian Noise (AWGN) processes having an average single-sided noise power per unit frequency of $N_0 = 4.0 \times 10^{-21}$ watts/Hz [6] in the SD and SR links, respectively. In this contribution, we have adopted the AAF model of [6] 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.

The signal received by the PU/DN under the DAF protocol via the Relay-to-Destination (RD) link can be formulated as:

$$Y_{rd}^{DAF} = \sqrt{P_{CR,1}} h_{rd} X + n_{rd} \ . \tag{3}$$

Similarly, the signal received by the PU/DN under the AAF protocol via the RD link may be expressed as:

$$Y_{rd}^{AAF} = \omega_A \sqrt{P_{CR,1}} h_{rd} Y_{sr} + n_{rd} \ , \tag{4}$$

where $\omega_A = \frac{1}{\sqrt{P_S |h_{sr}|^2 + N_0}}$ [10] is the amplification factor. 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 given by [10] [11]:

$$\begin{aligned} \sigma_{ab} &= \left(\frac{\lambda}{4 d_{ab} \pi} \right)^{\alpha} \ , \\ &= \left(\frac{c}{4 d_{ab} f_c \pi} \right)^{\alpha} \ , \end{aligned} \tag{5}$$

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 [12] 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. Without loss of generality, we assume $T_1 = T_2 = \frac{T}{2}$. Based on Shannon's capacity theorem, the CCMC capacity of the cooperative relay channel over the bandwidth of W_1 Hz is given by:

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

where we have $f_{CR} = \frac{P_S P_{CR,1} |h_{sr}|^2 |h_{rd}|^2}{(P_S |h_{sr}|^2 + P_{CR,1} |h_{rd}|^2 + N_0) N_0}$ [10], when the AAF protocol is employed, while the equivalent DAF function may be written as $f_{CR} = \frac{P_{CR,1} |h_{rd}|^2}{N_0}$. Based on Eq.6, the bandwidth required for achieving a transmission rate of $R_{PU} <= C_{PU}$ may be formulated as:

$$W_1 >= \frac{2 R_{PU}}{\log_2 \left[1 + \frac{P_S |h_{sd}|^2}{N_0} + f_{CR} \right]} \ . \tag{7}$$

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

$$C_{PU}^{*} = W_0 \log_2 \left[1 + \frac{P_{PU} |h_{sd}|^2}{N_0} \right] \ . \tag{8}$$

It can be shown that the transmission power originally required for achieving $R_{PU} = C_{PU}$ is given by:

$$P_{PU} = \frac{N_0 (2^{\frac{R_{PU}}{W_0}} - 1)}{|h_{sd}|^2} \ . \tag{9}$$

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 achievable transmission rate of the CUs is given by:

$$R_{CR} = W_2 \log_2 \left[1 + \frac{P_{CR,2} |h_{CR}|^2}{N_0} \right] \ , \tag{10}$$

where h_{CR} denotes the channel between a CU/SN and its CU/DN. If the total transmission power of CUs is limited to P_{CR}, then we have:

$$P_{CR} = \frac{1}{2} P_{CR,1} W_1 + P_{CR,2} W_2 \ . \tag{11}$$

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:

$$\psi = \frac{\frac{1}{2} P_{CR,1} W_1}{P_{CR}} \ , \tag{12}$$

where $\psi = [0 \quad 1]$. 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:

$$1 - \psi = \frac{P_{CR,2} W_2}{P_{CR}} . \tag{13}$$

More specifically, the transmission power $\mathrm{P}_{CR,1}$ at CU/RN may be determined from Eq. (7) and Eq. (12). On the other hand, the CU's own data rate using the released bandwidth $W_2 = W_0 - W_1$ may be derived as :

$$R_{CR} = (W_0 - W_1) \log_2 \left[1 + \frac{P_{CR} |h_{CR}|^2 (1 - \psi)}{(W_0 - W_1) N_0} \right] , \tag{14}$$

which can be optimized with respect to ψ. Moreover, the Reduced-Distance-Related-Pathloss-Reduction (RDRPR) [13], [14] in our system experienced by the SR link with respect to the SD link as a benefit of its reduced distance based path-loss can be computed as [13]:

$$G_{sr} = \left(\frac{d_{sd}}{d_{sr}} \right)^{3} \ . \tag{15}$$

Similarly, the RDRPR of the RD link with respect to the SD link can be formulated as:

$$G_{rd} = \left(\frac{d_{sd}}{d_{rd}}\right)^3 . \tag{16}$$

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. Practical ATTCM-aided Cooperative Cognitive Radio Scheme

In this section we propose an ATTCM aided cooperative CR scheme and consider how much of W_2 can be saved as a function of the SNR, when our ATTCM scheme is invoked.

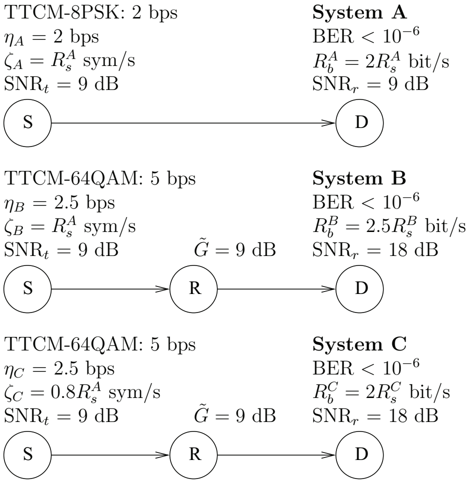

Fig. 2. Comparison of a non-cooperative scheme and two relay-assisted DAF schemes, where the target SNR_t is 9dB and the target BER is below 10^{-6}. The corresponding SNR_r values are obtained from Fig. 4.

Fig. 2 shows three examples of fixed mode transmissions, where System A is a non-cooperative system, while System B and System C are relay aided cooperative 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 given by $R_b = \eta R_s$ bit/s, where η is the throughput in terms of information bit per modulated symbol (BPS) whose unit is bit-per-symbol (bps). When considering a pathloss exponent of $\alpha = 3$, we have a RDRPR of $G = 2^\alpha = 8$, which is $\tilde{G} = 9$ dB when the RN is located at the mid-point between the SN and the DN. The received SNR in decibel is given by $\gamma_r = \gamma_t + \tilde{G}$ and the *transmit SNR*[1] is given by $\gamma_t = 10\log_{10}(\frac{P_t}{N_0})$, where P_t is the transmit power and N_0 is the single-sided noise power. We assume that a BER of 10^{-6} 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 $\eta_A = 2$ bps in System A, when using the same bandwidth of $\zeta = R_s$. 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:

$$\begin{aligned} R_s^C &= \frac{\eta_A R_s^A}{\eta_C} , \\ &= 0.8 R_s^A . \end{aligned} \tag{17}$$

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 pR_s^A, where $p = \frac{\eta_A}{\eta_C} = \frac{2}{2.5} = 0.8$ is the throughput ratio of System A to System C. More specifically, the bandwidth-reduction factor is given by:

$$B_s = 1 - \frac{\eta_A}{\eta_C} . \tag{18}$$

Therefore, a CU may serve as a RN between the first PU (SN) and the second PU (DN) in order to save 20% ($1 - 0.8 = 0.2 = 20\%$) of the bandwidth. The bandwidth saved can then be shared among other CUs. Having studied the above TTCM-8PSK and TTCM-64QAM fixed mode schemes, we will considered how our ATTCM may be exploited in our cooperative CR scheme. As shown in Fig. 3, we consider a single SN, one DN and K number of RNs. Each of the communication links is assisted by the ATTCM scheme. The signal received by node b from node a is given by:

$$Y_{ab} = \sqrt{G_{ab}}\sqrt{P_{ab}}h_{ab}X + n , \tag{19}$$

where G$_{ab}$ denotes the RDRPR experienced by the link between node a and node b, while h_{ab} represents to the quasi-static Rayleigh fading channel between two nodes. We consider the DAF protocol at each RN. The quasi-static Rayleigh fading channels between the SN and the RNs are denoted as $h_{sr_1}, h_{sr_2}, \ldots, h_{sr_K}$, while those between the RNs and the DN are represented by $h_{r_1d}, h_{r_2d}, \ldots, h_{r_Kd}$. We assume that the channel gains are independent of each other and the receive SNR at node b is given by:

$$\gamma_R = \frac{G_{ab}|h_{ab}|^2}{N_0} . \tag{20}$$

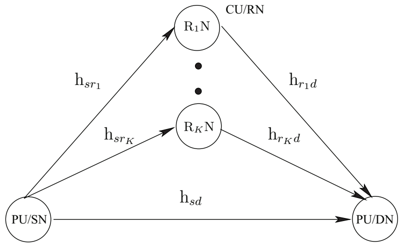

Fig. 3. The schematic of two-hop relay-aided system. Quasi-static Rayleigh fading channel between node a and node b is denoted as h_{ab}.

As seen from Fig. 3, we have $(K+1)$ links spanning from the SN to the DN supported by K RNs. We only choose one of the K RNs to assist the PU/SN. We denote the squared sum of the SR and RD channels via the kth RN as: $|h_{sr_kd}|^2 = |h_{sr_k}|^2 + |h_{r_kd}|^2$. The specific RN that exhibits the maximum value of $|h_{sr_kd}|^2$ from all the K RNs is selected for relaying. 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 in an AWGN channel, which is shown in Fig. 4. Specifically, the ATTCM mode switching operation and the throughput of the modes is based on the following algorithm:

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

---

[1] The concept of transmit SNR [14] 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.

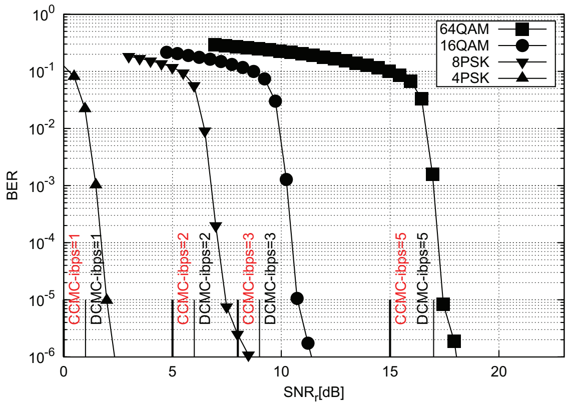

Fig. 4. The BER versus SNR$_r$ performance of TTCM using a frame length of 1200 symbols, when communicating over AWGN channels. Four TTCM iterations was invoked.

As seen from Fig. 4, we chose the switching thresholds to ensure that the BER at the RN is lower than 10^{-6}, which is given by Υ_{ATTCM}=[3, 9, 12, 18] dB. We note that Shannon's CCMC capacity is only restricted by the SNR and the bandwidth. The CCMC-based switching thresholds are represented as Υ_{CCMC}=[0, 5, 8, 15] dB, while the switching thresholds of the corresponding DCMC based scheme are given by Υ_{DCMC}=[1, 6, 9, 17] dB, which are also explicitly shown in Fig. 4.

III. THE PERFORMANCE AND RESULTS

A. Performance of the Idealistic Cooperative Cognitive Radio Scheme

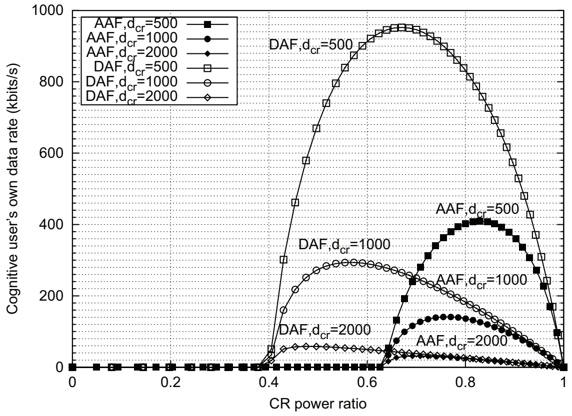

Fig. 5. The CU's own date date based on DAF and AAF detections, when the corresponding RDRPR factors are given by $G_{sd} = 1$, $G_{sr} = 8$ ($d_{sr} = \frac{d_{sd}}{2}$) and $G_{rd} = 1$ ($d_{rd} = d_{sd}$).

The relationship of the power ratio ψ and the data rate of CU is shown in Fig. 5 and Fig. 6.

Fig. 5 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$_0$ = 1MHz 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.9. We plotted the data rate of the CU based on three values of the distance d_{cr} between the CU and its own destination, namely 500m, 1km and 2km. Finally, the optimum ratios of the relay power over the total power budget when using the DAF protocol are given by 64.5%, 53% and 45%. Similarly, the optimum power ratios for the AAF protocol are given by 82%, 72% and 65%.

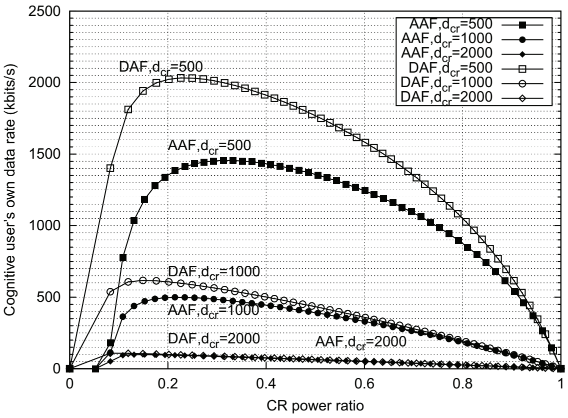

Fig. 6. The CU's own date date based on DAF and AAF detections, when the corresponding RDRPR factors are given by $G_{sd} = 1$, $G_{sr} = 8$ ($d_{sr} = \frac{d_{sd}}{2}$) and $G_{rd} = 8$ ($d_{rd} = \frac{d_{sd}}{2}$).

Fig. 6 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 $G_{sd} = 1$, $G_{sr} = 8$ and $G_{rd} = 8$. The optimum ratio of the relay power over the total power budget is 20%, 15% and 10% for d_{cr}=500m, 1km and 2km, respectively, when using DAF detection. The corresponding values for AAF detection are given by 33%, 20% and 12%. We found from Fig. 5 and Fig. 6 that when the CU/RN is half-way between the SN and the DN, a CU/RN only has to offer a smaller proportion of its transmission power to help the PU/SN. It was also found that as d_{cr} increases, the CU's own data rate drops due to its increased pathloss.

B. Performance of the Practical ATTCM-aided Cooperative Cognitive Radio Scheme

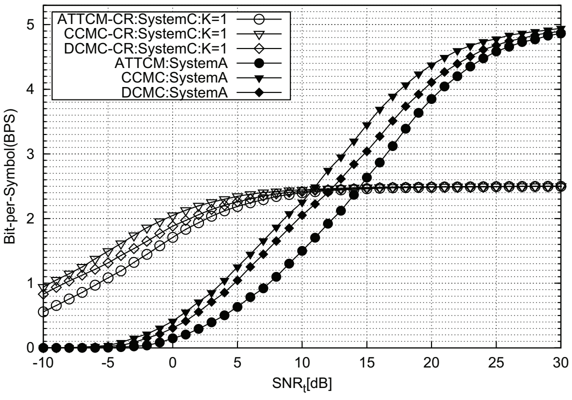

Fig. 7. The performance of the corresponding BPS value versus SNR$_t$ of the ATTCM-CR, CCMC-CR and DCMC-CR schemes when communicating over quasi-static Rayleigh fading channels. A BER below 10^{-6} is maintained and G$_{sr}$= G$_{rd}$ = 8. The "SystemC" is used to refer System C in Section II-B, while the "SystemA" is refer to the non-cooperation System A in Section II-B. **The number of RN is K=1.**

Fig. 7 shows the BPS value versus SNR_t of the ATTCM-CR, CCMC-CR and DCMC-CR schemes. The ATTCM-CR model is used for referring to the ATTCM-based cooperative CR scheme. Similarly, the notations CCMC-CR and DCMC-CR denote the cooperative CR schemes that are based on the CCMC and DCMC capacities, respectively. We use η_A to denote the throughput of System A and η_C to represent the overall throughput of System C. As seen from

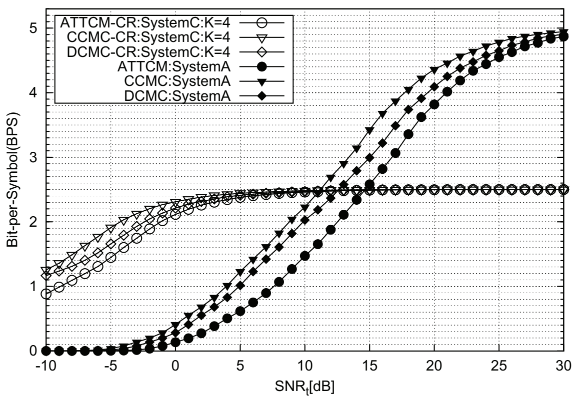

Fig. 8. The performance of the corresponding BPS value versus SNR$_t$ of the ATTCM-CR, CCMC-CR and DCMC-CR schemes when communicating over quasi-static Rayleigh fading channels. A BER below 10^{-6} is maintained and G$_{sr}$= G$_{rd}$ = 8. The "SystemC" is used to refer System C in Section II-B, while the "SystemA" is refer to the non-cooperation System A in Section II-B. **The number of RN is K=4.**

Fig. 7, the curves of η_A and η_C recorded for the CCMC-CR and DCMC-CR modes are close to each other, when employing only one RN. For SNR$_t \geq 30$ dB, the η_A value of the three schemes became saturated at 5 bps. In general, the CCMC-CR represents the upper bound, because the CCMC capacity is the highest. The intersection point of the η_A and η_C curves for the ATTCM-CR scheme is at SNR$_t$=14 dB, while those for the CCMC-CR and DCMC-CR modes are at 12 dB and 10 dB, respectively. When we have $\eta_C < \eta_A$ beyond the intersection point, cooperation is no longer beneficial. Hence, our cognitive system will employ System A when $\eta_A > \eta_C$. Observe from Fig. 8 that when the number of RNs is increased to $K = 4$, the η_C curve converges to the asymptotic value of 2.5 bps for $SNR_r \geq 5$ dB, which is 5 dBs earlier than its counterparts characterized in Fig. 7. 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.

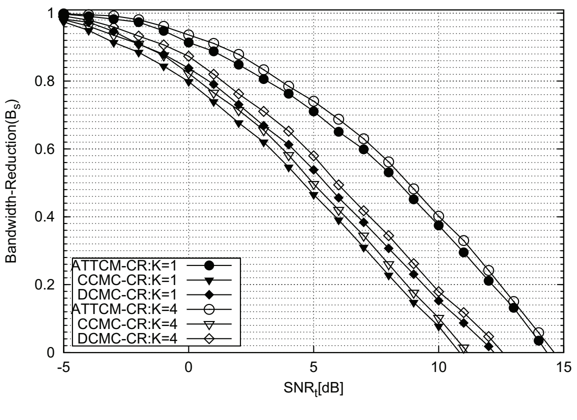

Fig. 9. The performance of the corresponding bandwidth-reduction value versus SNR$_t$ of ATTCM-CR, CCMC-CR and DCMC-CR schemes in System C, when communication over quasi-static Rayleigh fading channels. A BER of below 10^{-6} is maintained at DN and RDRPR is given by G$_{sr}$=G$_{rd}$=8. **The number of RNs are 1 and 4** .

Fig. 9 illustrates the attainable bandwidth-reduction (B$_s$) versus SNR_t for the ATTCM-CR, CCMC-CR and DCMC-CR schemes, when the number of RNs is given by one and four. As seen from Fig. 9, the bandwidth-reduction B_s is slightly higher, when the number of RNs is increased from one to four. It is also interesting to observe that the practical ATTCM-CR scheme is capable of reducing the bandwidth more substantially compared to the idealistic DCMC-CR and CCMC-CR 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 $\eta_A = 5$ 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 when $B_s > 0$. Note furthermore from Fig. 8 that at an SNR of 5 dB, the ATTCM-CR-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 2.4 bps. This may also be translated into a maximum bandwidth reduction of $(1 - \frac{0.6}{2.4}) = 0.75 = 75$ %.

IV. CONCLUSIONS

In this contribution, we have studied DAF and AAF assisted cooperative CR schemes and quantified the optimum power ratio required for achieving the best transmission throughput for the CU. We also proposed a practical ATTCM aided cooperative CR scheme, where adaptive coding and modulation were invoked according to the instantaneous channel conditions. We found that the proposed cooperative CR scheme enables the PU to transmit at an improved transmission rate at a given SNR, while releasing a significant amount of bandwidth for exploitation by the CUs, despite operating at a reduced SNR.

REFERENCES

[1] F.K. Jondral , "Cognitive radio: A communications engineering view," *IEEE, Wireless Communications* , vol. 14, pp. 28 –33, August 2007.

[2] J. Mitola and G. Q. Maguire, "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, vol. 6, pp. 13 –18, Aug 1999.

[3] N. Devroye and P. Mitran and V. Tarokh, "Achievable rates in cognitive radio channels," *IEEE Transactions on, Information Theory*, vol. 52, pp. 1813 – 1827, May 2006.

[4] Y. Li, "Distributed coding for cooperative wireless networks: An overview and recent advances," *IEEE, Communications Magazine*, vol. 47, pp. 71 –77, August 2009.

[5] O. Simeone and J. Gambini and Y. Bar-Ness and U. Spagnolini, "Cooperation and cognitive radio," in *2007. ICC '07. IEEE International Conference on, Communications*, pp. 6511 –6515, June 2007.

[6] Weifeng Su and J.D. Matyjas and S. Batalama, "Active cooperation between primary users and cognitive radio users in cognitive ad-hoc networks," in *2010 IEEE International Conference on, Acoustics Speech and Signal Processing (ICASSP)*, pp. 3174 –3177, March 2010.

[7] P. Robertson and T. Wörz, "Bandwidth-efficient turbo trellis-coded modulation using punctured component codes," *IEEE Journal on Selected Areas in Communications*, vol. 16, pp. 206–218, Feb 1998.

[8] L. Hanzo, T. H. Liew, B. L. Yeap, R. Y. S. Tee, and S. X. Ng, *Turbo Coding, Turbo Equalisation and Space-Time Coding(EXIT-Chart-Aided Near-Capacity Designs for Wireless Channels)*. John wiley-IEEE Press, 2011.

[9] S. X. Ng and L. Hanzo, "On the MIMO channel capacity of multidimensional signal sets," *IEEE Transactions on, Vehicular Technology*, vol. 55, pp. 528 – 536, March 2006.

[10] K. J. R. Liu, A. K. Sadek, W. Su and A. Kwasinski, *Cooperative Communications and Networking*. Cambridge University Press , New York, 2009.

[11] A. Goldsmith, *Wireless Communication*. Cambridge University Press, England, 2005.

[12] A. Tobagi Fouad and M. M. Hira, "Joint optimization of physical layer parameters and routing in wireless mesh networks," in *The 9th IFIP Annual Mediterranean, Ad Hoc Networking Workshop (Med-Hoc-Net), 2010* , pp. 1 –8, June 2010.

[13] L. Kong, S. X. Ng, R. Maunder, and L. Hanzo, "Maximum-throughput irregular distributed space-time code for near-capacity cooperative communications," *IEEE Transactions on, Vehicular Technology* , vol. 59, pp. 1511 –1517, March 2010.

[14] H. Ochiai, P. Mitran, and V. Tarokh, "Design and analysis of collaborative diversity protocols for wireless sensor networks," in *IEEE 60th, Vehicular Technology Conference, 2004. VTC2004-Fall. 2004*, vol. 7, pp. 4645 – 4649 Vol. 7, Sept. 2004.