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Adaptive Combined Channel-Network Coding for Cooperative Relay Aided Cognitive Radio Networks

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Abstract: Cognitive radio (CR) is one of the emerging technologies for 4G/5G applications. Cooperative relay communications and network coding are some techniques that helped in enhancing the CR applications. This paper considers a primary broadcasting system for multimedia video streaming applications that broadcasts data to the primary users and to an aiding cooperative relay CR secondary system. The cooperative overlay secondary system can use many error control coding techniques for point-to-point data retransmissions such as channel coding, network coding, and combined coding techniques to enhance the system performance under variable channel conditions. This work proposes a novel adaptive combined channel network coding (AC2NC) technique for data retransmissions. The new AC2NC first analyses the channel feedback information and then selects the best retransmission coding technique based on the targeted bandwidth or transmission time optimization. This is instead of using a single static channel or network coding technique with dynamic channel conditions. The proposed AC2NC improves the system throughput, decreases the retransmission time, and avails more spectrum access opportunities for the secondary system's own data transmissions. The AC2NC relative bandwidth and time saving opportunities for CR users can exceed 90% under certain channel conditions versus some static coding techniques.

Keywords: adaptive coding; AC2NC; cognitive radio; network coding; channel coding



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1. Introduction

Several error-control coding techniques can be used for reliable point-to-point data retransmissions under different channel conditions. Automatic repeat request (ARQ) is used with cyclic redundancy check (CRC) coding to ensure successful transmission. Forward error correction (FEC) codes are used to detect and correct errors in the received data. This decreases the data retransmissions and enhances the system capacity [1]. Hybrid automatic repeat request (HARQ) combines the FEC and ARQ coding techniques. The incremental redundancy HARQ (IR-HARQ) is another retransmission technique where the user data and some of the parity segments are transmitted. More additional parity segments are transmitted, if there are retransmission requests to recover the lost data [2–4].

Many studies focused on developing channel coding techniques to enhance the network capacity and decrease the transmission time. Information processing at intermediate network nodes was not considered in these studies until network coding (NC) was introduced as a promising technique for reliable data transmission. NC enhances the robustness of the wireless network and improves the throughput [5–7]. To have more error control coding benefits, joint channel network coding techniques are introduced in conjunction with HARQ in [8,9] to improve the performance compared with traditional error-control techniques. Joint network coding with Reed–Solomon (RS) is considered in [10,11] to improve the system performance of wireless networks.

Cooperative communications and cognitive radio networks (CRNs) are introduced to enhance system throughput and optimize spectrum utilization for wireless communication

systems, especially with spectrum scarcity challenges and license issues. Cognitive radio (CR) is proposed with many 4G/5G applications to create dynamic spectrum access opportunities for the unlicensed secondary user (SU) in the case licensed primary users (PUs) are not fully utilizing the spectrum. The evolution in antenna systems' design has been crucial in 4G/5G wireless applications. Modern antenna systems have more advanced and reconfigurable capabilities to cope with such applications' requirements [12–15].

Many CRN models for SU spectrum access techniques are considered underlay, overlay, and interweave [16,17]. With the underlay model, both SU and PU are allowed to transmit simultaneously; however, SUs' interference shall not exceed a specific limit to avoid impacting PU transmission. The overlay model allows concurrent PU and SU transmissions; the secondary CR system uses part of its power for its data transmission and the other part to relay PU transmissions cooperatively. This is to gain an opportunity to use the spectrum. For the interweave model or opportunistic model, the secondary system is only allowed to use non-utilized spectrum holes by the PUs at a specific time or location.

Cognitive radio is proposed to be applied in conjunction network coding and cooperative relaying [18–22] for different broadcasting and multicasting purposes, such as 5G wireless applications. This allows more users to access the spectrum, utilizes more bandwidth, and ensures more security. SUs can use NC via XORing different packets and transmit them, while the PU is inactive with available spectrum holes in less time and with a less needed capacity [17]. To handle the throughput-delay trade-off with variable channel conditions, some adaptive coding techniques are introduced to enhance throughput and delay for the broadcasting model as in [23] and for multiple sources and single destination as in [18,24].

This paper evaluates the broadcasting throughput and transmission time of channel coding, network coding, and combined coding techniques for a primary system with a different number of PUs and a cooperative CR secondary system. This broadcasting system is used for multimedia video streaming applications purposes via a centralized main primary base station (PBS) and a dedicated link to a secondary base station (SBS) cooperative relay near PUs to handle data retransmissions.

We propose a new adaptive combined channel network coding (AC2NC) technique for SBS. As the name indicates, it is an adaptive coding technique to reach the best performance based on channel feedback information under dynamic channel conditions. This offers more access opportunities for SBS own data transmission using the overlay model by availing more Bandwidth for the frequency division duplexing (FDD) transmission mode, in addition to more free transmission time for the time division duplexing (TDD) transmission mode. The sections of this paper are organized as follows. In Section 2, the broadcasting model with cooperative CRN (CCRN) with different numbers of PUs is presented. In Section 3, the analytical and theoretical models are presented. In Section 4, the simulation results are discussed. Finally, Section 5 summarizes the findings and concludes the work.

2. Broadcasting CCRN System Model

The broadcasting model introduces space diversity for cooperative cognitive radio network (CCRN) wireless transmission. We consider the broadcasting system model in Figure 1, where the licensed network with a PBS broadcasts the same data packets to all the M PUs. At the same time, the unlicensed CCRN with an SBS needs to communicate with an SU. The cooperative SBS node listens to the PUs' channel feedback to decide on the optimal retransmission technique for each PU. It has the software capabilities to allow for the novel adaptive combined coding technique for PUs' optimal data retransmissions. Cooperative SBS also has the cognitive radio capabilities to access spectrum for its own data transmission while the PBS is inactive. The PBS data packets are first transmitted via wireless channels (black solid lines) from the PBS to the different PUs and via a dedicated fiber link (black dashed line) to the cooperative SBS to help in relaying in case retransmission if needed. If packets are lost from the PUs, the PUs request the retransmission from the SBS cooperative

relay. Therefore, the SBS retransmits these packets to the targeted PUs. If the PU failed to recover the erroneous packet from the SBS cooperative relay after several trials (pre-defined), it requests a retransmission from the PBS. The cooperation target exchanges more spectrum access opportunities for the secondary system's own data transmissions using an overlay mode after the PUs' successful data transmission.

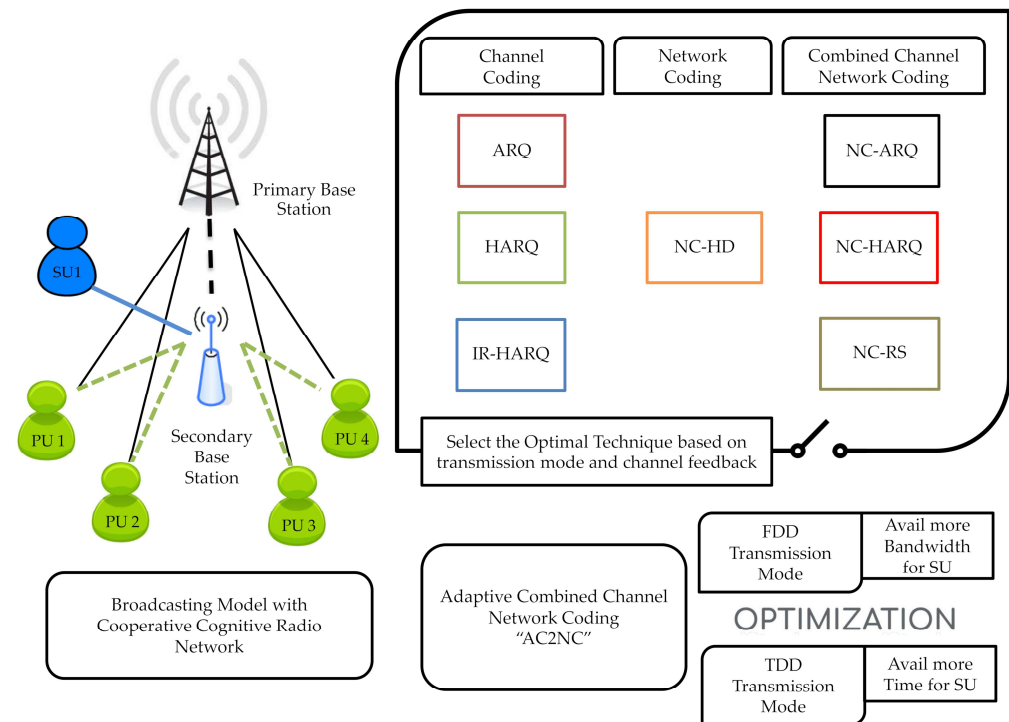


Figure 1. Broadcasting system model, single PBS, single SBS, and four primary users.

The following channel coding, network coding, and combined coding techniques are considered for the broadcasting model in our work:

- Automatic repeat request (ARQ)
- Hybrid automatic repeat request (HARQ Type I)
- Incremental redundancy HARQ (IR-HARQ)
- Network coding with hard decision (HD) decoding (NC-HD)
- Network coding with CRC for error detection (NC-ARQ)
- Combined channel network coding with HARQ (NC-HARQ)
- Combined channel network coding with Reed-Solomon (NC-RS) and HD for error detection

Then, we recommend the new adaptive combined channel network coding (AC2NC) model for CCRN using cooperative SBS, which decides the optimal error control coding technique based on the dynamic channel conditions.

For NC-RS as an example, the first transmission is encoded using RS error correction code at the PBS. At the PUs, the packets are decoded using the RS decoder. In reference to the PUs' acknowledge/negative acknowledge (ACK/NACK) channel feedbacks of different packets, NC is applied to recover the lost packets via cooperative SBS cooperative relay node. Hereby, SBS combines the maximum possible numbers of the PUs' lost data packets. These NC combined packets are encoded and rebroadcasted using RS in certain time slots from the SBS to all PUs until successful data delivery. Table 1 is an example of the lost packets "X" in the case of four PUs after the PBS first transmission.

Table 1. Received packets after the first transmission.

Time Slot	1	2	3	4	5	6	7	8	9	10	11
Transmitted	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
Received at PU1	P1	X	P3	P4	P5	X	P7	X	X	P10	P11
Received at PU2	X	P2	P3	P4	X	P6	P7	P8	X	X	P11
Received at PU3	P1	P2	X	P4	X	P6	X	P8	P9	P10	P11
Received at PU4	P1	X	P3	P4	X	P6	P7	P8	X	P10	X

To decrease the NC scheduling, in case two or more PUs lost the same data packet i.e., (P2, P5, and P9), it is retransmitted separately from PBS without combination. The lost packets from only one PU are subject to network coding with different combinations. As in Table 2, we combine a set of four packets (P6, P1, P3, and P11) and a set of three packets (P8, P7, and P10).

Table 2. Lost packets retransmissions using NC–RS.

Time Slot	12	13	14	15	16
Transmitted	$P6 \oplus P1 \oplus P3 \oplus P11$	$P8 \oplus P7 \oplus P10$	P2	P5	P9
Received at PU1	P6	P8	P2	-	P9
Received at PU2	P1	P10	-	P5	P9
Received at PU3	P3	P7	-	P5	-
Received at PU4	P11	-	P2	P5	P9

Each PU recovers the lost packets via XORing the NC combined packets with the earlier successfully received packets within the NC combination at the same PU. As an example, PU1 extracts P6 by XORing NC combined packet with the earlier received packets at PU1 (P1, P3, and P11).

The cooperative SBS uses the AC2NC technique and selects one of the considered error-control coding techniques under different channel conditions. This is to achieve the optimal throughput for the FDD transmission mode or the optimal transmission time for the TDD transmission mode.

3. Analytical Model

In our work, the broadcasting throughput is considered as the ratio between the original PBS data and the total required data to deliver it to all the PUs; either via the direct PUs channels or via the SBS cooperative relay. Our model consists of a single PBS and M PUs. We assume that the PBS broadcasts K data bits to all PUs, and the SBS cooperative relay simultaneously receives these K data bits error free. The SBS cooperative relay node uses one of the considered techniques adaptively for data retransmissions and coding according to the channel feedback. We consider N as the total number of the required data bits to have successful transmission of K either from PBS or SBS. N has a different length according to the different coding techniques used.

For ARQ, the PBS data bits are firstly broadcasted with the CRC r_1 bits. N_{ARQ} is the total ARQ transmitted data bits and $E(Y_{ARQ})$ is the expected value of the total number of ARQ transmissions. The broadcasting throughput of ARQ is given by Equation (1):

$$\eta_{ARQ} = \frac{K}{N_{ARQ}} = \frac{K}{(K + r_1) * E(Y_{ARQ})} \quad (1)$$

For HARQ, N_{HARQ} is the total HARQ transmitted data bits. N_{FEC} is the number of FEC parity bits and $E(Y_{HARQ})$ is the total number of HARQ data transmissions. The HARQ broadcasting throughput is given by Equation (2):

$$\eta_{HARQ} = \frac{K}{N_{HARQ}} = \frac{K}{(K + r_1 + N_{FEC}) * E(Y_{HARQ})} \quad (2)$$

For IR–HARQ, $N_{IR-HARQ}$ is the total IR–HARQ transmitted data bits. N_{FEC} is divided into $L - 1$ parity segments. With more requested data retransmissions, the parity bits segments are transmitted one by one. Let $E(Y_0 = j_0)$ be the expected value of the required transmissions for $N_0 = K + r_1$ bits to reach j_0 . $E(Y_i = j_i)$ is the expected value of the required transmissions to all PUs for N_i parity segments to reach j_i . The IR–HARQ broadcasting throughput is given as in Equation (3):

$$\eta_{IR-HARQ} = \frac{K}{N_{IR-HARQ}} = \frac{K}{\sum_{i=0}^L N_i * E(Y_i = j_i)} \quad (3)$$

The broadcasting throughput for NC–HD, NC–ARQ, and NC–RS is shown in Equations (4)–(6):

$$\eta_{NC-HD} = \frac{K}{N_{NC-HD}} = \frac{K}{K * E(Y_{NHD})} = \frac{1}{E(Y_{NHD})} \quad (4)$$

$$\eta_{NC-ARQ} = \frac{K}{N_{NC-ARQ}} = \frac{K}{(K + r_1) * E(Y_{NARQ})} \quad (5)$$

$$\eta_{NC-RS} = \frac{K}{N_{NC-RS}} = \frac{K}{(K + N_{FEC}) * E(Y_{NRS})} \quad (6)$$

where N_{NC-HD} is the total NC–HD transmitted data bits, and $E(Y_{NHD})$ is the total number of NC–HD transmissions. N_{NC-ARQ} is the total NC–ARQ transmitted data bits, and $E(Y_{NARQ})$ is the total number of NC–ARQ transmissions. N_{NC-RS} is the total NC–RS transmitted data bits and $E(Y_{NRS})$ is the total number of NC–RS transmissions.

For NC–HARQ, the broadcasting throughput is given as Equation (7):

$$\eta_{NC-HARQ} = \frac{K}{N_{NC-HARQ}} = \frac{K}{(K + r_1 + N_{FEC}) * E(Y_{NHARQ})} \quad (7)$$

where $N_{NC-HARQ}$ is the total NC–HARQ transmitted data bits and $E(Y_{NHARQ})$ is the required NC–HARQ transmissions to deliver the PBS original data to all PUs.

For FDD transmission mode, the AC2NC optimization target is to avail more bandwidth, and more spectrum access opportunities for SBS's own data transmission. This is done using the optimal coding technique with maximum throughput at different channel conditions. We find the AC2NC optimal throughput η_{AC2NC} can be given by Equation (8):

$$\eta_{AC2NC} = \left(\min \left\{ \begin{array}{l} \left(1 + \frac{r_1}{K}\right) * E(Y_{ARQ}), \\ \left(1 + \frac{r_1}{K}\right) * E(Y_{NARQ}), \\ \left(1 + \frac{r_1 + N_{FEC}}{K}\right) * E(Y_{HARQ}), \\ \left(1 + \frac{r_1 + N_{FEC}}{K}\right) * E(Y_{NHARQ}), \\ \sum_{i=0}^L \frac{N_i}{K} * E(Y_i = j_i), E(Y_{NHD}), \\ \left(1 + \frac{N_{FEC}}{K}\right) * E(Y_{NRS}) \end{array} \right\} \right)^{-1} \quad (8)$$

This is applied for different numbers of PUs as well as different channel conditions. The relative bandwidth saving of AC2NC compared with the “Q” considered coding techniques is presented in Equation (9):

$$BW_{Saving_Q} = 1 - \left\{ \frac{\eta_Q}{\eta_{AC2NC}} \right\} \quad (9)$$

In TDD transmission mode, the AC2NC optimization target is to avail more transmission time for SBS's own transmission. AC2NC decides on the optimal coding data

transmission technique with minimum transmission time for different channel conditions to decrease the PU's transmission time. Hence, we illustrate a generic model for AC2NC optimal transmission time T_{AC2NC} as follows in Equation (10):

$$T_{AC2NC} = \min \left\{ \begin{array}{l} E(Y_{ARQ}), E(Y_{NARQ}), \\ E(Y_{HARQ}), E(Y_{NHARQ}), \\ E(Y_{NHD}), \sum_{i=0}^L E(Y_i = j_i), \\ E(Y_{NRS}) \end{array} \right\} \quad (10)$$

AC2NC relative time saving versus the "Q" different considered coding techniques is shown in Equation (11):

$$T_{Saving_Q} = 1 - \left\{ \frac{T_{AC2NC}}{T_Q} \right\} \quad (11)$$

4. Results and Discussion

We use simulations to validate our analytical model for the AC2NC technique versus the considered error-control coding techniques. We assume that the same data packets are transmitted from the PBS to the different PUs through AWGN channels in a broadcasting CCRN model with an SBS cooperative relay. The PUs' channel feedback (ACK/NACK) is assumed as error-free and shared with the SBS and PBS (if needed). MATLAB is used to evaluate the system throughput for different signal to noise ratio (SNR) via simulating the AWGN channels with two and four PUs. For error detection coding, CRC-19 is used. For error correction coding, RS (127,123) is used.

Figure 2 shows the broadcasting throughput simulation versus theoretical results for four PUs with a single SBS relay. NC-RS offers higher throughput when assessed versus NC-HARQ for different channel conditions. For low SNR, NC-HARQ is better than IR-HARQ as it has more FEC segments in such bad conditions. For SNR moderate range, IR-HARQ has higher throughput than NC-HARQ. With a high SNR range, NC-HD offers the best broadcasting throughput as it does not have extra error correction or detection headers.

Figure 3 shows the number of transmissions for simulation versus the theoretical results to deliver the PBS data packets for four PUs. A lower number of retransmissions is needed using NC-RS with different channel conditions. IR-HARQ has a more significant number of transmissions, especially with low and moderate SNR ranges, as parity segments are sent in more time slots. The simulation results are close to those from the theoretical model discussed in Section 3.

Figure 4 shows the relative bandwidth saving percentage of AC2NC compared with the other considered coding techniques with four PUs and different channel conditions. AC2NC selects the best error-control coding technique for the FDD transmission mode to avail more bandwidth for the SBS's own transmission.

Figure 5 reveals the relative transmission time-saving advantage of AC2NC compared with the different assessed coding techniques. AC2NC targets the optimal coding technique for the TDD transmission mode with the least transmission time to avail more time for the SBS's own transmission.

Figure 6 shows the AC2NC FDD optimal retransmission mode with different channel conditions for the SBS cooperative relay for two and four PUs. The AC2NC selects NC-RS at bad and moderate channel conditions (less than 8.5 dB) for the FDD transmission mode. With highly moderate SNR, AC2NC selects IR-HARQ (from 8.5 dB). The AC2NC switches to NC-HD with good channel conditions to avail more spectrum access opportunities for SBS's own data transmission (from 10 dB) with two PUs. For four PUs, the AC2NC transition to NC-HD transmission mode is faster (from 9.5 dB).

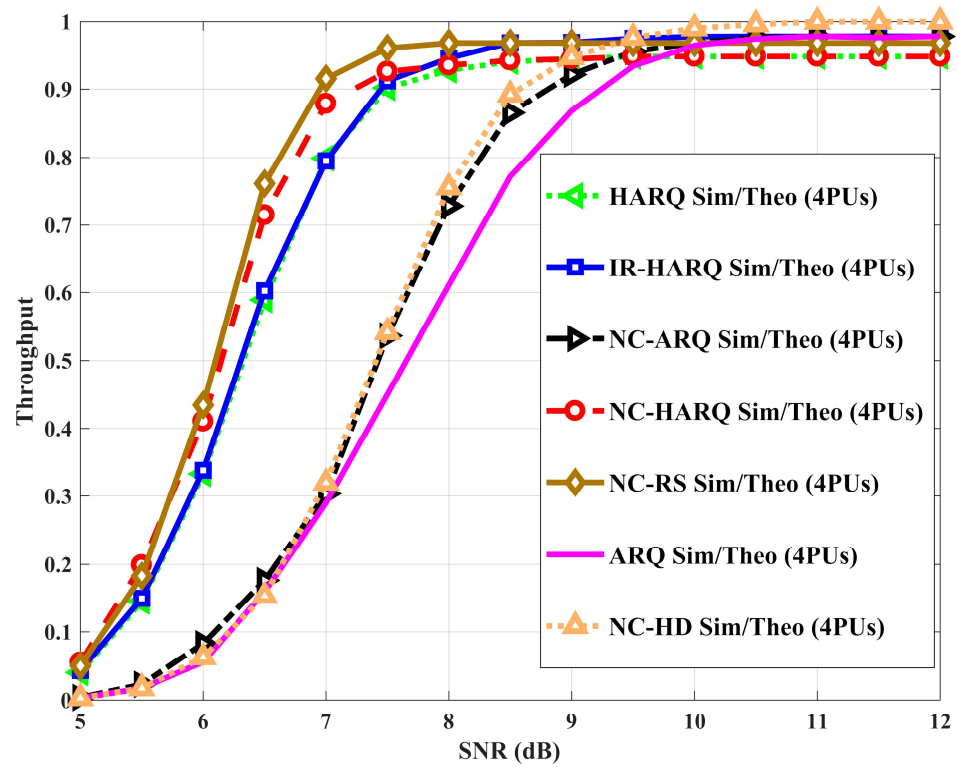


Figure 2. Broadcasting throughput comparison.

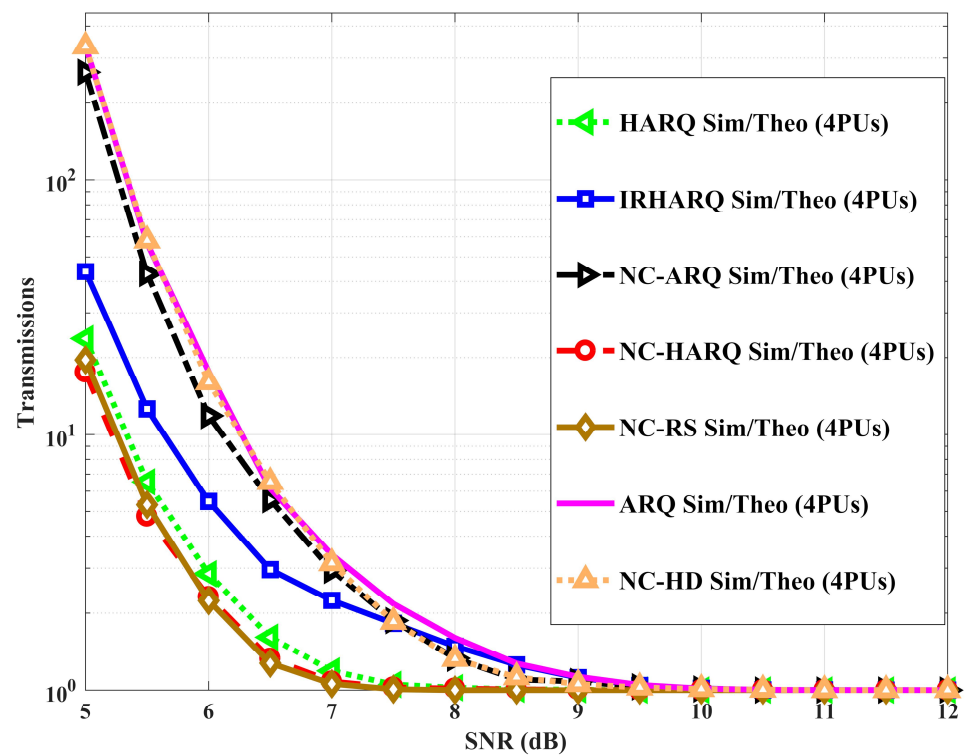


Figure 3. Broadcasting transmission times comparison.

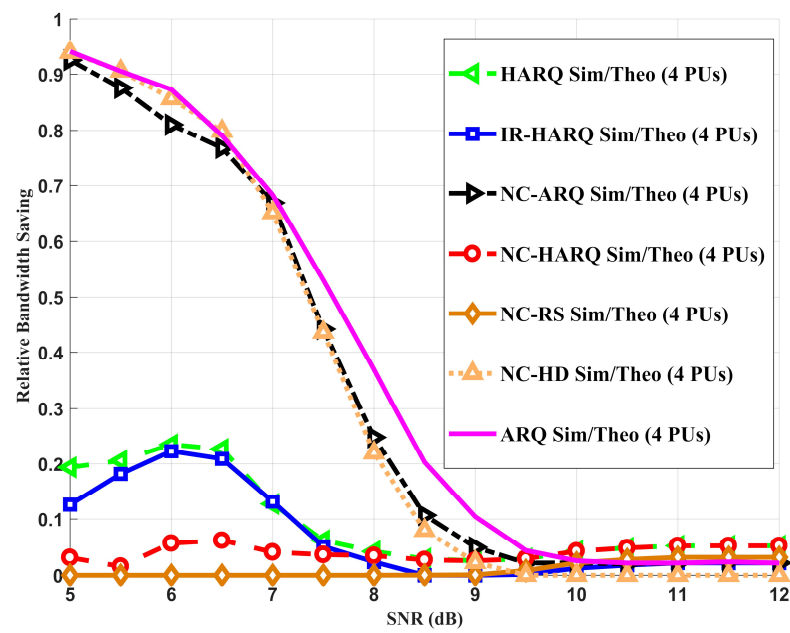


Figure 4. AC2NC relative bandwidth saving.

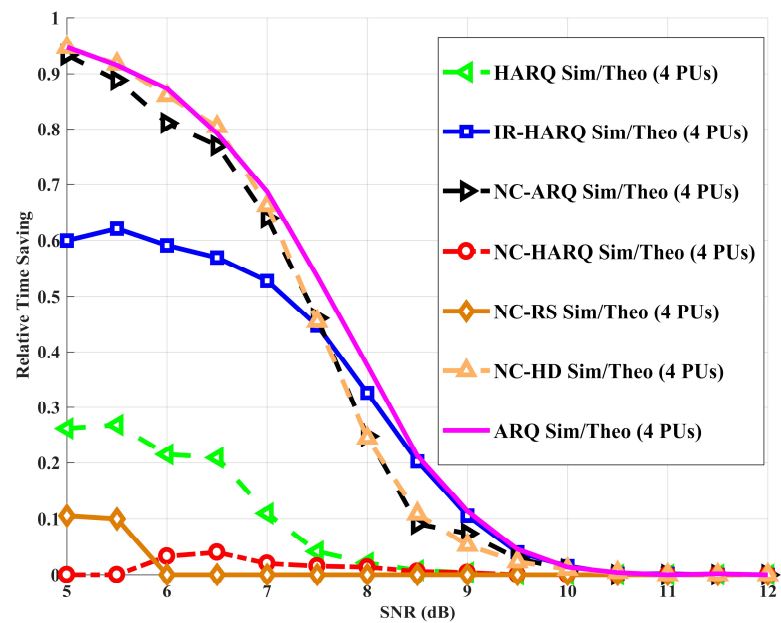


Figure 5. AC2NC relative time saving.

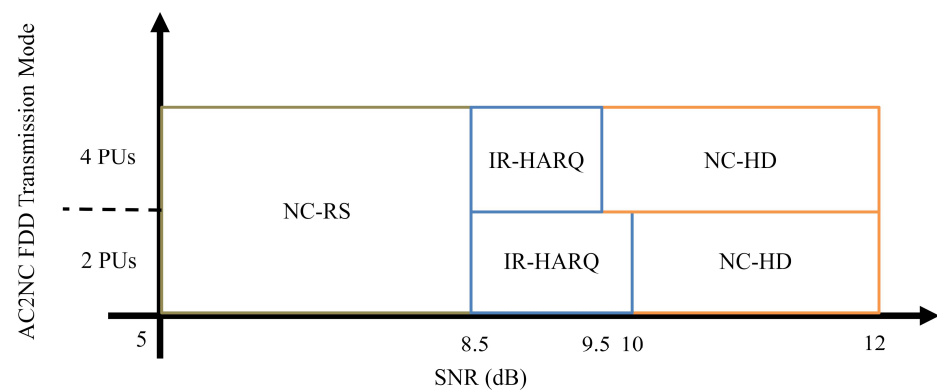


Figure 6. AC2NC FDD transmission mode.

Table 3 shows the percentage of the relative bandwidth saving gain of AC2NC versus all considered static coding techniques with different channel conditions for four PUs. The techniques with 0% gain at the different channel conditions represent the AC2NC FDD optimal transmission mode to support the SBS's own transmission. All other gains represent the benefit of using our proposed AC2NC technique.

Table 3. AC2NC relative bandwidth saving gain—four PUs.

Technique	SNR											
	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5
ARQ	94%	91%	87%	79%	68%	53%	37%	20%	10%	4%	3%	2%
HARQ	19%	21%	23%	23%	13%	6%	4%	3%	3%	3%	4%	5%
IR-HARQ	13%	18%	22%	21%	13%	5%	2%	0%	0%	0.1%	1%	2%
NC-HD	94%	91%	86%	80%	65%	44%	22%	8%	2%	0%	0%	0%
NC-ARQ	93%	88%	81%	77%	67%	44%	25%	11%	5%	2%	2%	2%
NC-HARQ	3%	2%	6%	6%	4%	4%	3%	3%	3%	3%	4%	5%
NC-RS	0%	0%	0%	0%	0%	0%	0%	0.02%	0.1%	1%	2%	3%

For the TDD transmission mode as shown in Figure 7, AC2NC uses NC-HARQ for four PUs under a very bad SNR level (less than 6 dB) and then switches to NC-RS for bad and moderate levels (from 6 to 9.5 dB). AC2NC can select either NC-RS or HARQ for four PUs with a highly moderate SNR range (from 9.5 to 11 dB) as both offer a similar transmission time performance. AC2NC prefers NC-HD with good channel conditions (from 11 dB) to utilize the benefit of both bandwidth and time-saving opportunities. For two PUs, the AC2NC TDD transmission mode uses NC-RS for bad and moderate levels (less than 8.5 dB). From 8.5 to 11 dB, AC2NC can select HARQ or NC-RS. With good channel conditions (higher than 11 dB), NC-HD is preferred.

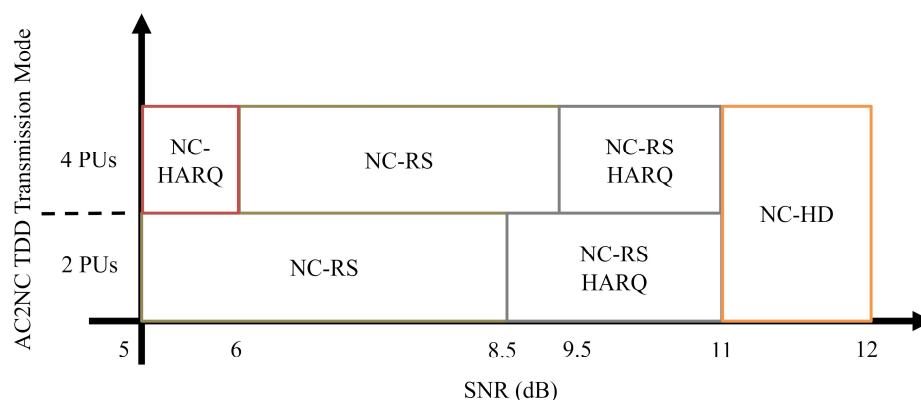


Figure 7. AC2NC TDD transmission mode.

Table 4 shows the percentage of the relative time saving gain of AC2NC versus the considered static coding techniques with different SNR for four PUs. The techniques with 0% gain represent the possible AC2NC TDD optimal transmission modes at different SNR. For a good SNR range of more than 11 dB, we find that many techniques can be used. However, we prefer NC-HD for its mutual bandwidth and time saving gains to avail more opportunities for SBS's own data.

Table 4. AC2NC relative time saving gain—four PUs.

Technique	SNR												
	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11
ARQ	95%	92%	87%	79%	69%	54%	38%	21%	11%	5%	1%	0.4%	0%
HARQ	26%	27%	22%	21%	11%	4%	2%	1%	0.4%	0%	0%	0%	0%
IR–HARQ	60%	62%	59%	57%	53%	45%	33%	20%	11%	4%	2%	0.2%	0.2%
NC–HD	95%	92%	86%	80%	66%	46%	24%	11%	5%	2%	1.0%	0.4%	0%
NC–ARQ	93%	89%	81%	77%	67%	45%	26%	12%	6%	2%	1%	0.2%	0%
NC–HARQ	0%	0%	3%	4%	2%	2%	1%	1%	0.4%	0%	0%	0%	0%
NC–RS	11%	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

5. Conclusions

This paper presented a novel adaptive combined channel network coding (AC2NC) technique for overlay cooperative cognitive radio networks while using the secondary base station (SBS) to relay the PUs' transmissions. The proposed AC2NC technique selected the best error-control coding technique from assessed channel coding, network coding, and combined coding techniques. AC2NC adopted its transmission mode to achieve the best throughput or the best transmission time under variable channel conditions with different numbers of primary users. This provides more spectrum access opportunities and more free transmission time for SBS's own data transmissions. The AC2NC technique has the best performance among all other static coding techniques for FDD- and TDD-based transmission modes. Meanwhile, there are some scheduling complexity challenges for using AC2NC with large-scale systems and more PUs/SUs. However, such challenges can be managed by improving the SBS software processing capabilities via software-defined radio (SDR).

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