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Invited Article

Network Coding with Multimedia Transmission and Cognitive Networking: An Implementation based on Software-Defined Radio

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Abstract– **Network coding (NC) is considered a breakthrough to improve throughput, robustness, and security of wireless networks. Although the theoretical aspects of NC have been extensively investigated, there have been only few experiments with pure NC schematics. This paper presents an implementation of NC under a two-way relay model and extends it to two non-straightforward scenarios: (i) multimedia transmission with layered coding and multiple-description coding, and (ii) cognitive radio with Vandermonde frequency division multiplexing (VFDM). The implementation is in real time and based on software-defined radio (SDR). The experimental results show that, by combining NC and source coding, we can control the quality of the received multimedia content in an on-demand manner. Whereas in the VFDM-based cognitive radio, the quality of the received content in the primary receiver is low (due to imperfect channel estimation) yet retrievable. Our implementation results serve as a proof for the practicability of network coding in relevant applications.**

Keywords– **Network coding, two-way relay model, software-defined radio (SDR), orthogonal frequency division multiplexing (OFDM), Vandermonde frequency division multiplexing (VFDM), multimedia, cognitive radio.**

1 INTRODUCTION

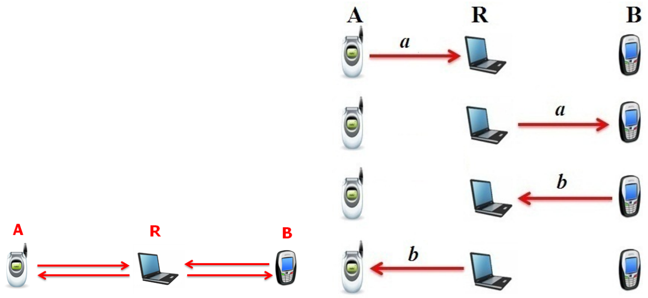
In 2000, network coding (NC) was first introduced by Ahlswede in [1] to improve network throughput. Unlike the store-and-forward mechanism in traditional routing protocols, NC allows intermediate nodes between source and destination to perform additional computations (coding) on the incoming data before forwarding the coded information.

There are two main NC schemes, namely straightforward network coding (SNC) where coding is performed on digital bit streams after they have been received [2], and physical-layer network coding (PNC) where coding is performed via the additive nature of simultaneously arriving electromagnetic waves [3], [4]. The latter was shown to achieve a higher throughput performance as illustrated in the following example.

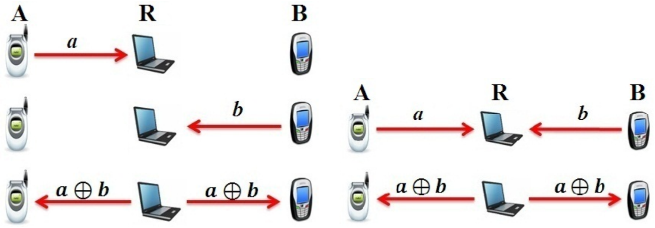
Let us consider a two-way relay (TWR) model depicted in Figure 1a, which is a simple and popular network topology. In this model, two end nodes A and B expect to exchange their respective data packet a and b with each other via a relay node R. It is assumed that there is no direct link between A and B due to, e.g., blockage and limited radio range. We consider three communication schemes.

First, following a traditional store-and-forward scheme, the network needs four time slots to complete the packet exchange, as illustrated in Figure 1b. Specifically, A transmits packet a to R in the first time slot, and R forwards a to B in the second time slot. Then, B transmits packet b to R in the third time slot, and R forwards b to A in the fourth time slot. Note that node R merely forward the packets without processing the data contents.

Second, following SNC, as illustrated in Figure 1c, the number of time slots can be reduced. The relay node R first receives sequentially both packets a and b, then performs the bit-wise exclusive OR (XOR) operation,



(a) TWR model (b) Conventional: 4 time slots



(c) SNC: 3 time slots (d) PNC: 2 time slots

Figure 1. Conventional forwarding and network coding methods in the TWR model.

denoted by $\oplus$, over these packets to produce a new single packet $a \oplus b$. In the third time slot, node R simply broadcasts this coded packet. The two end nodes can recover their expected packet based on their own packet and the received coded packet. Specifically, A can recover b as $b = a \oplus (a \oplus b)$ and B can recover a as $a = b \oplus (a \oplus b)$. In this way, SNC reduces the number of time slots to three, achieving a 33% throughput gain.

Finally, following PNC, illustrated in Figure 1d, A and B transmit simultaneously. Their packets are combined *on the air* due to the additive nature of the electromagnetic waves. Node R properly processes the received signal in order to produce the coded packet before forwarding in the second time slot. Therefore, PNC requires only two time slots, achieving a 50% throughput gain compared to the traditional store-and-forward routing scheme.

Although NC has been widely analyzed and assessed via both theoretical analyses and numerical simulations, limited results have been obtained via real-channel implementation. One of the first implementations of NC was reported in [5], where a simplified version of PNC, called analog network coding (ANC), was introduced.

The idea of ANC is that the relay node simply amplifies then retransmits the received superimposed signals without coding. This implementation was based on a software-defined radio (SDR) platform consisting of the Universal Software Radio Peripheral (USRP) with RFX2400 daughterboards as the hardware and the open source GNU Radio [6] as the signal processing software.

Although ANC is simple to implement, it has a critical drawback of error propagation since the relay amplifies the noise along with the signal before forwarding. PNC systems in which the relay performs XOR or other denoising PNC mappings on the received signals are preferred since they yield significant performance improvements.

The first successful implementation of PNC was reported in [7]. However, this system operates in an offline manner. The first real-time PNC implementation was introduced in [8], based on USRP N210 with XCVR2450 boards. In this system, frequency division duplex (FDD) was employed to separate the uplink and the downlink. To overcome some implementation challenges such as synchronization, packet detection, channel estimation, and carrier-frequency-offset (CFO) estimation, the authors used orthogonal frequency division multiplexing (OFDM) with beacons. In addition, PHY-layer forward error control and MAC-layer ARQ error control were also used to improve reliability. However, this implementation requires a change in the frame format and a balance between the power of the end nodes' signals received at the relay.

Another implementation of NC was presented in [9]. This prototype is for SNC and half-duplex packet switching, also based on USRP with RFX2400 daughterboards. Some other recent implementations of network coding can be found in, for example, [10], [11].

In this paper, we present an SDR-based implementation of NC under the TWR model and two extended network models for multimedia transmission and cognitive radio, respectively. Our main contributions are three-fold. First, we implement NC under the TWR model operating in full-duplex transmission mode. In our scheme, we let node A and node B transmit in separated frequencies in the first time slot, and the relay node performs the XOR operation on digital bit streams and then broadcasts the XOR-ed packet in the second time slot. Compared to existing implementations of NC under the TWR model, our scheme combines the advantages of both SNC and PNC; that is, it requires only two time slots while avoiding complex PNC mapping. Furthermore, the proposed scheme can be easily integrated into existing systems since it does not require any change in the frame format. We also implement an error correction code to improve the reliability. Second, we present the first implementation of NC for multimedia transmission with joint source-network coding. Two types of source coding are considered: layered coding and multiple-description coding. NC is employed to ensure that the destination can still receive data packets when the direct link is lost. Finally, we present the first implementation of NC for a special cognitive radio network based on Vandermonde frequency division multiplexing (VFDM). Specifically, we consider a TWR model in the secondary tier of an overlay two-tier network. To avoid cross-tier interference to the primary receiver, the relay node uses VFDM to transmit signals on the nulls of the primary channel.

The rest of the paper is organized as follows. Section 2 describes our NC framework and prototype, as well as three scenarios whose implementations are subsequently presented. Specifically, Section 3 presents the implementation of NC under the TWR model. Section 4 extends the implementation of NC, combining source coding with multimedia transmission. Section 5 presents the implementation of NC in the VFDM-based cognitive radio network. Finally, Section 6 gives concluding remarks.

2 PROPOSED NETWORK CODING FRAMEWORK AND PROTOTYPE

2.1 Proposed Network Coding Framework

Following the principle of NC, we present a framework in which relay nodes are inserted in the network to detect and exploit coding opportunities to forward multiple packets in a single transmission in order to improve network throughput and reliability. Consider a general mesh network of which each node has packets to transmit and would like to receive packets from certain other nodes. Our considered framework incorporates the following features.

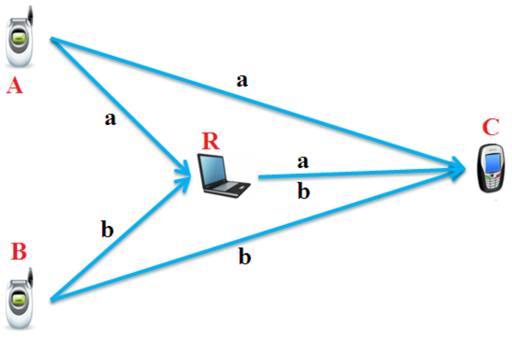
Relaying infrastructure: Relay nodes are deployed in the network to help forward the packets. These nodes are placed at positions where there is no direct link between the communicating nodes due to blockage or limited radio range, or specially designed so as to maximize the coding gain.

Opportunistic listening: Exploiting the broadcast nature of wireless media, the relay nodes opportunistically listen to the packets transmitted from surrounding nodes. It is assumed that each node includes its identity and the identities of the other nodes from which it would like to receive packets. Thus, the relay nodes can detect this information from the packets.

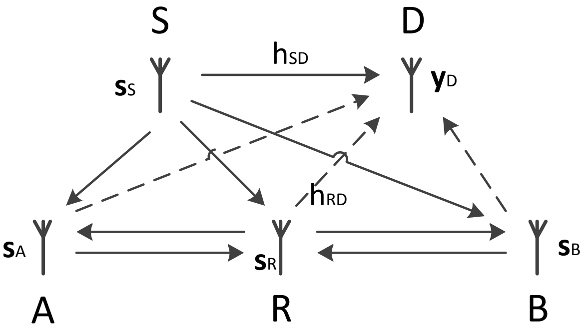
Opportunistic coding: From knowledge of the desired packets of each node, each relay node identifies the opportunity to encode a subset of the received packets to form a coded packet and broadcast this coded packet. Since there can be multiple coding options corresponding to multiple subsets of the received packets, the coding operation should be well designed. On one hand, the relay nodes should maximize the number of single packets encoded to reduce the transmission time. On the other hand, these coded packets should enable the intended nodes to decode their desired packets. For example, under the TWR model introduced in Section 1, after the first phase, the relay has received packets a and b from nodes A and B, respectively. It further knows that node A has packet a while desiring packet b, and that node B has packet b while desiring packet a. Therefore, a coding opportunity occurs, and the optimal coding operation is to combine a and b and send this combination, $a \oplus b$. In general, a subset of received packets should be combined if all the intended nodes already have all packets in the subset but one packet that they desire. Note that the number of encoded single packets, so-called the coding field size, can be larger than 2. The field size goes up linearly with the number of nodes in the network.

2.2 Proposed Prototype

Within the described framework, we design a prototype with the following elements. First, the nodes transmit their packets using OFDM. Second, in order for the relay nodes to simultaneously receive the packets, the communicating nodes employ FDD. Specifically, they shift their carrier frequency by a small amount from a central frequency using a frequency mixer, so that their signals are separated. The relay nodes receive at the central frequency and sample with a sufficiently wide bandwidth so as to recover the packets of multiple nodes. Third, we use an SDR platform that consists of bladeRF hardware [12] and GNU Radio software. Each node is a commodity personal computer running GNU Radio and connected to one or more bladeRF-x115 devices. The bladeRF devices operate in the full-duplex mode with two associated VERT 2450 antennas for transmission and reception.



(a) A 4-node network model



(b) A 2-tier cognitive radio network

Figure 2. Two scenarios of interest for NC implementation, apart from the TWR model.

We consider three scenarios of NC for implementation as follows. The first scenario is the TWR model presented in Section 1, where nodes A and B would like to exchange packets with the help of a relay. The second scenario, shown in Figure 2a, is a 4-node network where nodes A and B would like to send packets to a destination node, C, with the help of a relay. We assume that the packets from nodes A and B are generated from a specific type of source coding for multimedia transmission. The third scenario, shown in Figure 2b, is a two-tier cognitive radio network with a transceiver pair at the primary tier and a TWR model at the secondary tier. In these scenarios, we restrict the NC operation to a field size of 2, i.e., the relay node combine the incoming packets from two nodes.

We would like to emphasize that our prototype is the first case study of the interplay among network coding, source coding, OFDM and cognitive radio.

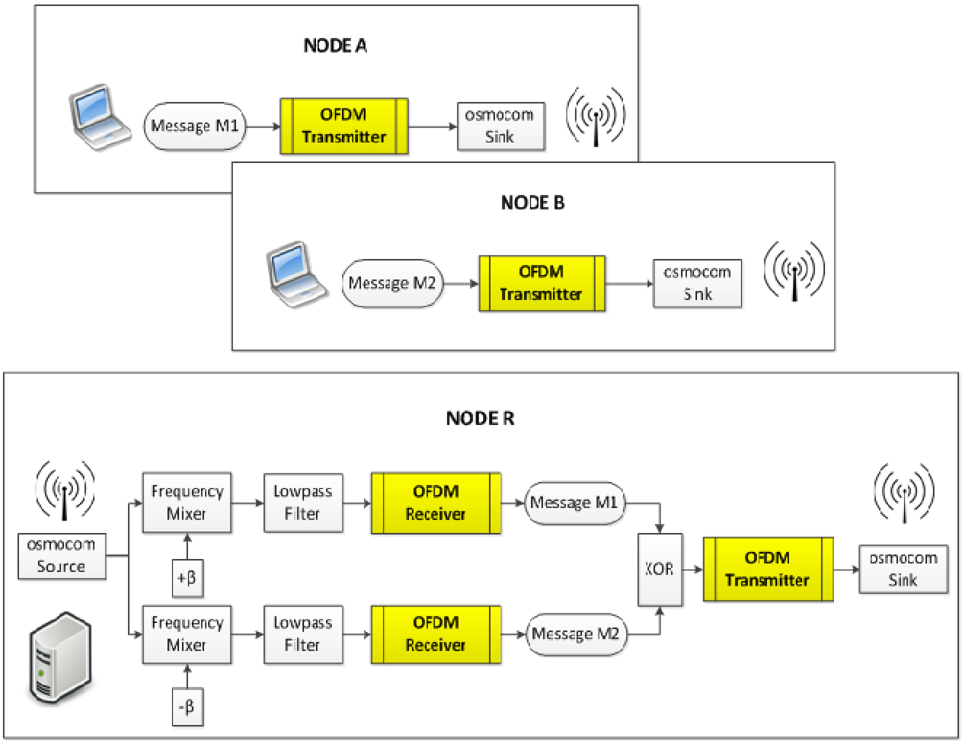


Figure 3. A system block diagram of the TWR model.

In our implementation, we use the version 3.7.6 of GNU Radio running in a dual-core general purpose processor under Ubuntu 14.04 OS. Experiments take place in a 25 m^2-area closed laboratory. We place the devices at least 0.5 m away from each other. We make use of the OFDM tranceiver blocks developed in the *gr-s4a* module [13]. Further details about the experimental setup are given in each following section, where we present sequentially the implementation of the three aforementioned scenarios.

3 IMPLEMENTATION OF NETWORK CODING UNDER THE TWR MODEL

In this section, we focus on an SDR-based real-time implementation of NC under the TWR model.

3.1 System Model

We consider the TWR model described in Section 1. To obtain reliable transmission, we need to overcome several challenges, in particular: (i) separation of uplink signals at the relay node, (ii) time and frequency synchronization, and (iii) channel estimation.

Our solutions respectively are: (i) use frequency division multiplexing to distinguish uplink signals at the relay node, (ii) employ OFDM and exploit the preamble part for time and frequency synchronization following the Schmidl-Cox synchronization method, and (iii) insert pilot symbols in an OFDM frame for channel estimation. Next, we will describe these solutions.

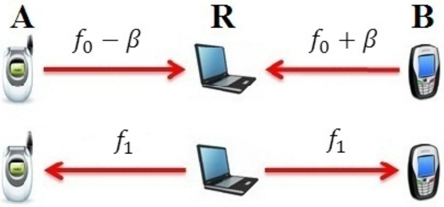


Figure 4. Frequency allocation in the TWR model.

3.1.1 Separation of Uplink Signals:

Figure 4 illustrates the frequency allocation in our implementation. Let f_0 be a (high) carrier frequency. Node A transmits on frequency $f_0 - \beta$ while node B on frequency $f_0 + \beta$. Node R transmits on another frequency f_1. Node R receives on frequency f_0, but samples with a wide bandwidth enough to completely receive both $f_0 - \beta$ and $f_0 + \beta$ so that node R can retrieve signals transmitted from nodes A and B separately.

Figure 3 depicts a signal processing block diagram of the TWR model. In particular, at node R, the input signal received at f_0 goes through two separate branches. In one branch, the input signal is shifted by an amount of β Hz at a frequency mixer, and then the mixed signal is low-pass filtered to retrieve the signal transmitted by node A. Similarly, in the other branch, the input signal is shifted by $-\beta$ Hz at another frequency mixer, and then the mixed signal is low-pass filtered to retrieve the signal transmitted by node B. The messages obtained in the two branches after OFDM demodulation are then combined into a new message by the XOR operation. This new message is then modulated and broadcast to A and B.

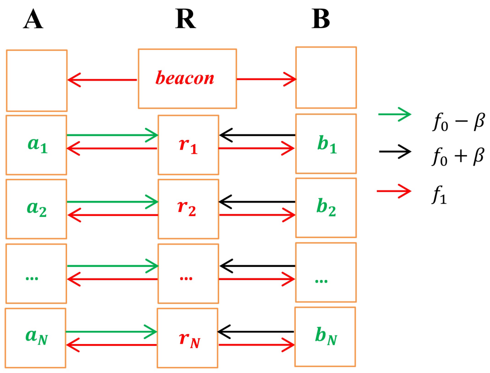


Figure 5. System operating mechanism.

3.1.2 Communication Protocol:

Our system works in *sessions*. The transmission protocol within each session is illustrated in Figure 5. The relay node first broadcasts a beacon message to tell the two end nodes the start of a session. When a session starts, each end node loads N native packets and stores them in a buffer. After that, a checking index i runs from 0 to $N-1$. At each value of i, the end node checks whether it has received the corresponding i-th XOR-ed packet from the relay or not. If yes, the checking index increases one. If no, the end node transmits the i-th native packet and then i is increased by one. If $i = N$, but the end node has not received all N XOR-ed packets yet, it will be returned to zero ($i = 0$). Of course, for the first run of the index i through the buffer, the end node certainly has to send all the loaded native packets. Thus, this protocol allows the end nodes to proceed to the transmission of the next native packet without having to wait for the successful transmission of the corresponding XOR-ed packet from the relay.

At the relay node, whenever it receives a native packet from an end node, it will check whether the corresponding native packet from the other end node is received. If yes, and the XOR-ed packet has not been created yet, the relay node will combine the two corresponding native packets into a XOR-ed packet and store it in a buffer. If no, the received native packet is just stored in a buffer. The XOR-ed packet is broadcast when it is available. A new session starts whenever both end nodes have received all N XOR-ed packets.

3.1.3 Error Correction Code:

To improve the communication reliability, we deploy a Hamming (7,4) code with the following generator matrix:

$$G = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}. \tag{1}$$

This means that three redundant bits are inserted in the first, second and fourth positions. A 4-bit message is encoded into a 7-bit codeword. At the receiver, the decoder calculates the syndrome metric and estimates the transmitted message. This Hamming code is able to correct one bit error.

(a) Transmited image at node A (b) Transmited image at node B

(c) Received image at node A, BER = 0.0128 (d) Received image at node B, BER = 0.0122

Figure 6. Transmitted and received images under the implemented TWR model.

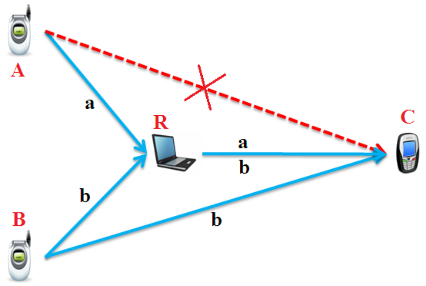
3.2 SDR Implementation and Results

As mentioned earlier, we make use of the *gr-s4a* module [13] for OFDM modulation and demodulation. To make the system work with the operating mechanism described above, we develop some controller blocks for the two end nodes and the relay node. We demonstrate the exchange of two images between the two end nodes. Each end node transmits a 256 × 256 image. An instance of transmitted and received images is shown in Figure 6. It is observed that the transmitted images from a node were well retrieved at the other node with a bit error rate (BER) of around 10^{-2}.

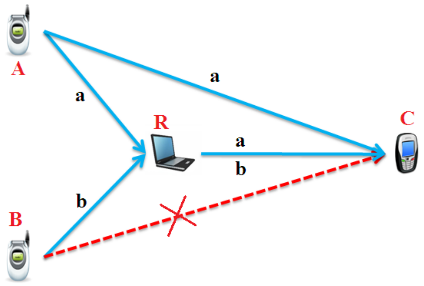
4 IMPLEMENTATION OF JOINT SOURCE-NETWORK CODING

Based on the implementation of NC under the TWR model described in Section 3, we extend the implementation to a 4-node network with joint source-network coding to show the usefulness of NC for multimedia transmission.

We consider two types of source coding. The first type is layered coding (LC), which is widely used in multimedia source coding. It generates one base layer and some n enhanced layers. The base layer is the most important layer and essential for the data stream to be recovered. Without receiving the base layer, the data stream cannot be recovered since the use of other enhanced layers depends on the content of the base layer. The enhanced layers are to improve the quality of the data stream. However, the first enhanced layer depends on the base layer and each enhanced layer $n+1$ depends on enhanced layer n. Thus a certain

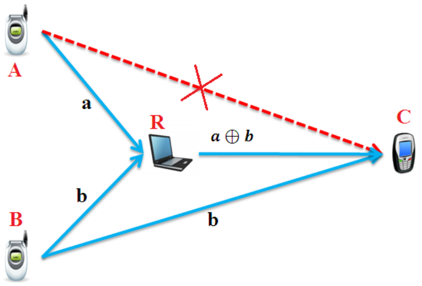


(a) Direct link *A*-*C* is lost

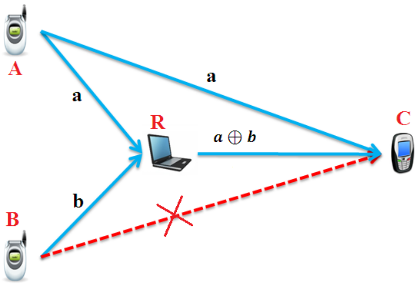


(b) Direct link *B*-*C* is lost

Figure 7. 4-node network model with conventional relay.



(a) Direct link *A*-*C* is lost



(b) Direct link *B*-*C* is lost

Figure 8. 4-node network model with NC.

layer n can only be applied if $n-1$ layers were already applied. Hence, data streams using this layer coding approach can be interrupted whenever the base layer is missing.

The second type of source coding is multiple-description coding (MDC) in which the data stream is divided into n independent sub-streams ($n \geq 2$), these sub-streams are called descriptions. Thus, MDC is a form of data partitioning. The packets of a description can be sent over different paths. In contrast to LC where the use of layer n depends on layer $n-1$, every received description of MDC at the destination can be used to recover the original data stream. This means that the quality of the decoded stream is proportional to the number of received descriptions. Since any received description can be used for the decoding process, the data stream is rarely interrupted (except for link loss). The loss of some descriptions only results in reduced quality of the decoded stream.

4.1 System Model

4.1.1 A 4-node Network Coding System Model: We consider a wireless network model with 4 nodes illustrated in Figure 2a, in which nodes A and B are two source nodes, node C is the destination, and node R is the relay. Both A and B want to send data to C and both have the direct link to C. Node R works as a relaying station with the aim of assisting the data transmission of A and B. Node R will relay all of its received packets to node C. The presence of node R in the system is to improve the possibility of receiving data packets at C in case a direct link is lost between A and C (link A-C) or between B and C (link B-C).

Consider the situation in which the above 4-node network model employs only traditional relaying. Suppose that one of the two direct-links (A-C or B-C) is lost, as illustrated in Figure 7. The links A-R, B-R, and R-C are supposed to be stable. It can be seen that, thanks to the addition of the relaying station (node R), C can still receive packets transmitted from A and B even when one of the two direct-links is lost because when node R is active, it relays every packet it receives to C.

Now, consider the 4-node network model with NC as shown in Figure 8. Node R will perform NC on two packets it received (a and b) to create a new packet, which is $a \oplus b$, and then forward this new packet to C. Suppose that the link between A and C (A-C) is lost as in Figure 8a. At node C, based on the packet b received directly from B and the XOR-ed packet received from R, the packet a can be recovered as $a = b \oplus (a \oplus b)$. Similarly, if the link B-C is lost, b can be recovered as $b = a \oplus (a \oplus b)$. Thus, if one of the two direct-links is lost, using NC, node R simply relays the XOR-ed packet to C without knowing which link is lost and still ensures that C can recover both a and b. Recall that for the case of using the conventional relaying mechanism, node R has to transmit both a and b since it does not know which direct-link is lost.

4.1.2 A 4-node Joint Source-Network Coding Model: Now, we combine source coding (at A and B) with NC (at R), as shown in Figure 9.

We assume that the direct-link B-C is lost. Each source node (A or B) transmits a layer (or a description). Node R performs NC over the two received packets (a and b) to create a new coded packet c as follows:

$$c = a \oplus \beta b, \tag{2}$$

where $\beta \in \{0, 1\}$. We consider the following two cases:

- *Case 1:* Node R does not have any information about packet b, meaning that b is considered as a normal data packet, β is set to be 0 or 1 with equal probabilities.

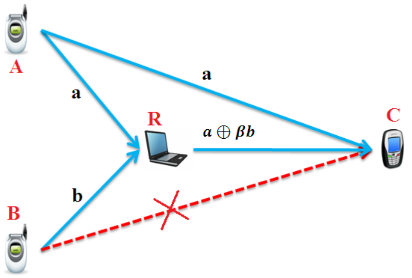


Figure 9. NC with source coding in 4-node network model.

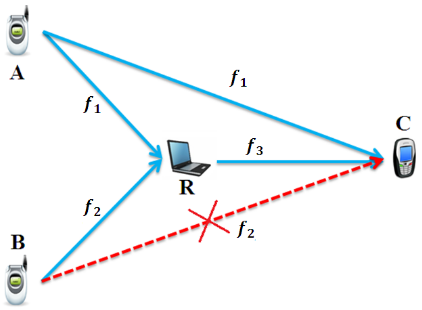


Figure 10. Frequency allocation in 4-node network model.

- *Case 2:* Node R has information about packet b, i.e., R knows if the packet b is of a layer or a description. Essential for the decoding process at C, the parameter β is set to be 1. This is to give priority to packets transmitted from B.

Figure 10 illustrates the frequency allocation of this 4-node network model. Here we still suppose that the direct-link B-C is lost. The two source nodes A and B transmit on frequencies f_1 and f_2, respectively. Node R receives on f_1 and f_2, and transmits on f_3. Since the link B-C is supposed to be lost, node C can only receive signals on f_1 and f_3. In addition, node C makes use of a controlling channel f_4 to transmit control messages to A and B. Packets transmitted from A and B will be combined into a XOR-ed packet to be relayed on f_3. All nodes in the network apply OFDM modulation and demodulation techniques.

This 4-node network also works in sessions. A session starts when node C sends a control message on f_4 to nodes A and B. Therefore, A and B know when to start a session and send their data. Whenever received the control message, end nodes (A, B) will load N packets and then store them in a buffer. After that, end nodes will send N packets continuously until receiving the next control message for the next session.

4.2 SDR Implementation and Results

(a) Decoded image using 1 description, BER = 0.1269

(b) Decoded image using 2 descriptions, BER = 0.000203

(c) Decoded image without information about source coding, BER = 0.2673

(d) Decoded image with information about source coding, BER = 0.0108

Figure 11. Decoded images by LC and MDC.

In our implementation, LC/MDC is first performed in Matlab to generate text files containing the layers/descriptions. Then, the controller block of source nodes in GNU radio software loads a text file corresponding to a layer/description and sends it. For simplicity, we implement LC with only two layers (the base layer and one enhanced layer). The data to be coded is a grayscale image. The base layer is generated by filtering the image with a lowpass filter, and the enhanced layer is generated by having the original image subtracted by the base layer. We build a block in GNU Radio for decoding at the destination so that the image can be recovered directly in GNU Radio. Similarly, for MDC, we implement MDC with only two descriptions. Received descriptions at the destination are used to recover the original image. This is done by a block in GNU Radio. For the case of LC, A transmits the enhanced layer and node B transmits the base layer. For the case of MDC, node A transmits one description and node B transmits the other description. Each source node is a commodity PC connected to a bladeRF device. For two nodes R and C, each node is a PC connected to two bladeRF devices.

Experimental results are shown in Figure 11. It is clearly seen that the decoded image quality is increased as more descriptions/information about source coding are used in decoding.

5 IMPLEMENTATION OF VFDM-BASED COGNITIVE RADIO WITH NETWORK CODING

Cognitive radio has been attracting a sustained attention for its potential to improve spectral efficiency. Cognitive radio enables the deployment of a two-tier network, composed of a primary tier and a secondary tier. The former is licensed to use a specific spectrum range, whereas the latter accesses this spectrum to carry their transmission without interfering primary transmissions. To avoid cross-tier interference to primary users, secondary users must adapt their transmission under some constraints in terms of signal power and

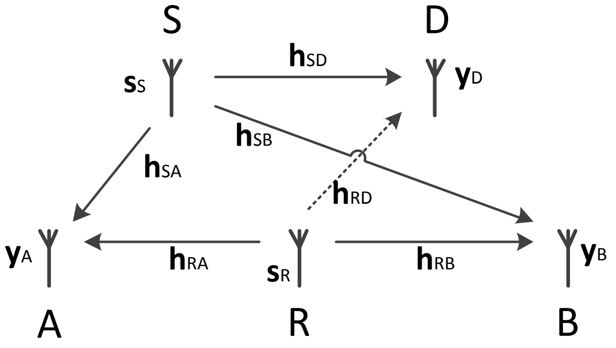


Figure 12. A transmission phase of the cognitive radio network.

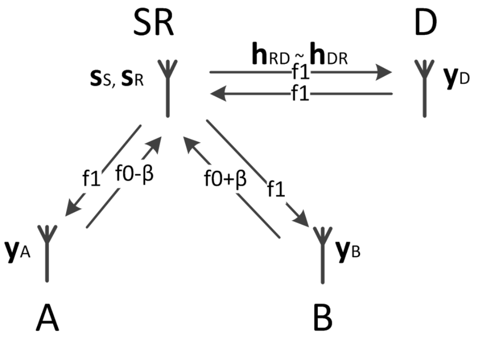


Figure 13. A 4-node hybrid cognitive radio network model.

channel access time. However, these constraints make reliable transmission challenging for secondary users. To guarantee an acceptable reliability for the secondary transmissions, NC, with its potential to improve the network throughput and shorten the transmission time, can be applied at the secondary tier.

Based on the overlay approach, VFDM was proposed in [14] as a technique for cross-tier interference management. With VFDM, a secondary transmitter uses linear precoding to project its signal onto the null space of the interfering channel from the secondary transmitter to the primary receiver. Therefore, the secondary transmitter can transmit over the same band as the primary transmitter but does not cause any interference at the primary receiver.

There have been some results on VFDM implementation in a VFDM standalone transceiver pair [15] or a two transmitter – two receiver scenario, where both transmitters are implemented on the same baseband transceiver, called hybrid transceiver [16]. This hybrid transceiver approach for cognitive network deployment was proposed in [17].

In this section, we present an implementation of a two-tier cognitive network adopting NC at the secondary tier.

5.1 System Model

Consider a 5-node two-tier network scenario, as shown in Figure 2b, where a primary system composed of a transceiver pair denoted by S (source)/D (destination), shares the spectrum with an opportunistic secondary system which is a TWR network composed of two end nodes A, B and one relay node R. The primary system communicates a message $\mathbf{s}_S$ over the licensed frequency band, whereas the secondary system access this spectrum to exchange two messages $\mathbf{s}_A$ (from A) and $\mathbf{s}_B$ (from B) between two end nodes via the relay node.

Consider the first phase of this network depicted in Figure 12, where S performs an OFDM transmission towards D with N subcarriers and a cyclic prefix (CP) of size L. The total block length is $N+L$. Node R performs a VFDM transmission with the same size of $N+L$.

Let $\mathbf{s}_S \in \mathbb{C}^N$, $\mathbf{s}_R \in \mathbb{C}^L$ be the transmit symbol vector at S and R, respectively, $\mathbf{F} \in \mathbb{C}^{N\times N}$ the unitary discrete Fourier transform (DFT) matrix with $[\mathbf{F}]_{k+1,l+1} = \frac{1}{\sqrt{N}} e^{-i2\pi\frac{kl}{N}}$, $k,l = [0,1,...,N-1]$, $\mathbf{A}$ the CP insertion matrix of size $(N+L)\times N$, $\mathbf{E} \in \mathbb{C}^{(N+L)\times L}$ the VFDM precoder matrix.

The precoded transmit vector $\mathbf{x}_S$ and $\mathbf{x}_R \in \mathbb{C}^{N+L}$ at S and R, respectively, are defined as follows:

$$\mathbf{x}_S = \mathbf{A}\mathbf{F}^{-1}\mathbf{s}_S \tag{3}$$

$$\mathbf{x}_R = \mathbf{E}\mathbf{s}_R. \tag{4}$$

Let $\mathbf{h}_{MN} = [h_{MN,0}, \ldots, h_{MN,L}]$ be the $(L+1)$-tap fading channel vector, modeling the downlink between the transmitter M and the receiver N. The convolution of each precoded symbol vector $\mathbf{x}_M$ with corresponding channel $\mathbf{h}_{MN}$ can be modeled as a Toeplitz matrix $\mathbf{H}_{MN} \in \mathbb{C}^{(N+L)\times(N+L)}$. The received signal $\mathbf{y}_D \in \mathbb{C}^N$, $\mathbf{y}_A \in \mathbb{C}^{N+L}$ and $\mathbf{y}_B \in \mathbb{C}^{N+L}$ at D, A and B, are respectively

$$\mathbf{y}_D = \mathbf{F}\mathbf{B}\big(\mathbf{H}_{SD}\mathbf{x}_S + \mathbf{H}_{RD}\mathbf{x}_R + \mathbf{n}_D\big) \tag{5}$$

$$\mathbf{y}_A = \mathbf{H}_{SA}\mathbf{x}_S + \mathbf{H}_{RA}\mathbf{x}_R + \mathbf{n}_A \tag{6}$$

$$\mathbf{y}_B = \mathbf{H}_{SB}\mathbf{x}_S + \mathbf{H}_{RB}\mathbf{x}_R + \mathbf{n}_B \tag{7}$$

where $\mathbf{B} = [\mathbf{0}_{N\times L}\mathbf{I}_N]$ is the CP removal matrix, $\mathbf{n}_M$ is the Gaussian noise vector at receiver $M \in \{A,B,D\}$ with covariance matrix $\sigma^2\mathbf{I}$.

By analyzing the interference constraint that R must satisfy, $\mathbf{E}$ can be built so that no interference signal component is perceived at D after the CP removal and DFT. Let $\tilde{\mathbf{H}}_{RD} = \mathbf{F}\mathbf{B}\mathbf{H}_{RD}$. For a zero cross-tier interference, the following condition must be satisfied:

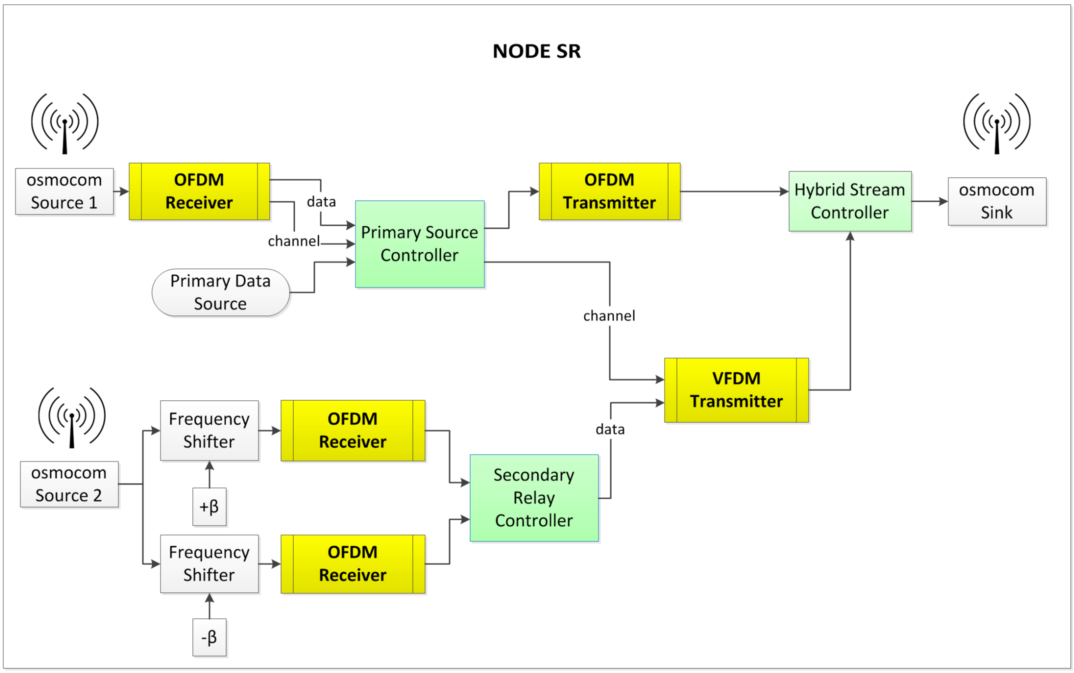
$$\tilde{\mathbf{H}}_{RD}\mathbf{x}_R = \tilde{\mathbf{H}}_{RD}\mathbf{E}\mathbf{s}_R = \mathbf{0}_N. \tag{8}$$

This is achieved by a special Vandermonde matrix construction of the linear procoder $\mathbf{E}$, built from the roots of the polynomial $S(z)$ with $L+1$ coefficients of the interference channel $\mathbf{H}_{RD}$ as $S(z) = \sum_{i=0}^{L} h_{RD,i} z^{-1}$.

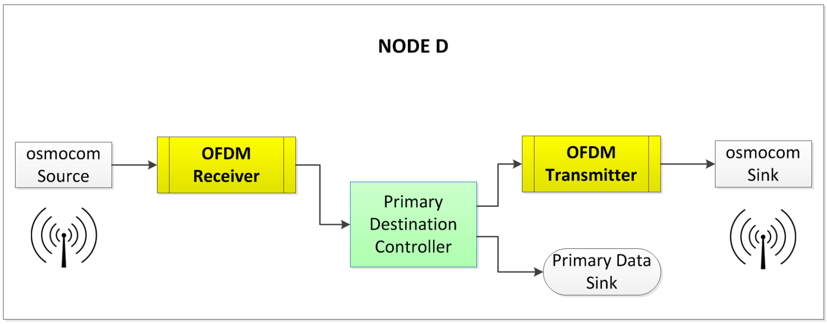
5.2 SDR Implementation

5.2.1 Baseband design:

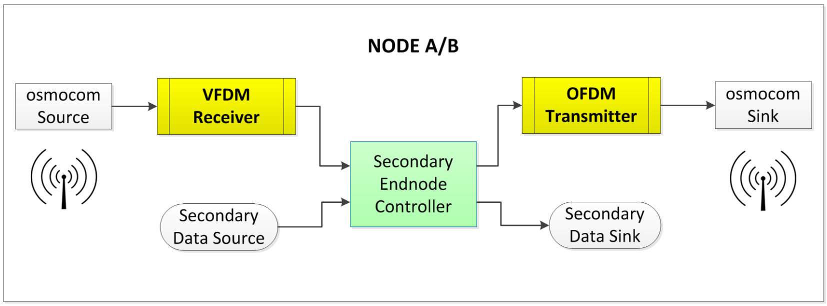
We consider the hybrid transceiver approach [17]. The primary transmitter S and the secondary relay R are implemented on one baseband transceiver. Consequently, the aforementioned 5-node network model is transformed into a 4-node hybrid network model as shown in Figure 13. The hybrid transceiver is denoted as SR. In



(a) Node *SR*



(b) Node *D*



(c) Nodes *A*, *B*

Figure 14. Signal processing chains of nodes in the considered cognitive radio network.

the implementation test-bed, it is a PC connected to two bladeRF devices. The main motivation for this hybrid approach is that the channel estimate of the primary link can be directly used to build the precoding matrix **E** for the VFDM transmission.

Each node operates following a specific configuration, depending on its transmitting/receiving mode in uplink/downlink phase and its role in the network. The operating modes and frequency allocated of each node are given in Table I. An illustration of the signal processing chain in each node is shown in Figure 14. The main algorithms for cognitive transmission strategy are embedded in controller blocks (in green).

Table I
Operating Mode and Frequency Allocated of Nodes for Uplink and Downlink Phases

Node	Uplink	Downlink
SR	OFDM RX, f_1	OFDM TX + VFDM TX, f_1
D	OFDM TX, f_1	OFDM RX, f_1
A	OFDM TX, $f_0 - \beta$	VFDM RX, f_1
B	OFDM TX, $f_1 + \beta$	VFDM RX, f_1

5.2.2 *Communication Protocol:*

We hereafter describe simply the adopted protocol in the order of channel access. The network operates under the channel reciprocity principle in TDD mode.

In the uplink phase, D sends a message $\mathbf{s}_S$ to SR at the center frequency f_1. This can be either a beacon message to trigger the communication or an ACK message to confirm the successful reception from SR in the previous downlink phase. In both cases, pilot symbols are added to enable the estimation of $\mathbf{H}_{DR}$ at SR. At SR, thanks to the principle of channel reciprocity, $\mathbf{H}_{DR}$ can be used as $\mathbf{H}_{RD}$ by the VFDM transmitter to construct the precoder $\mathbf{E}$. Meanwhile, in the secondary tier, the end nodes A and B send their message $\mathbf{s}_A$ and $\mathbf{s}_B$, respectively, to SR at the center frequency $f_0 + \beta$ and $f_0 - \beta$, respectively. These signals are carried by frequencies different from that carrying the signal from D and thus cause no interference to the latter. Node SR receives the primary signal from D at center frequency f_1 and receives the secondary signals at center frequency f_0 with wide-enough sampling bandwidth to capture both signals from A and B.

In the downlink phase, as soon as SR receives the signal from D, the downlink phase starts. Both OFDM frame containing the primary data for primary transmission and VFDM frame containing XOR-ed version of received messages from A and B for secondary transmission are generated at SR. Two frames are combined for a hybrid frame to be transmitted at f_1. All the receiving nodes D, A and B receive this frame but demodulate in their custom mode (OFDM or VFDM) to extract their intended data. To be more specific, D demodulates in the OFDM mode while A and B demodulate in the VFDM mode. Afterwards, an ACK message containing a pilot is generated at D to be transmitted back to SR in the next uplink phase in order to acknowledge the successful reception and trigger the next session. The secondary end nodes retrieve the data from the other end node from the received XOR-ed message from SR and its original data.

5.3 Experimental Results

In the experiment, we consider carrier frequencies $f_1 = 2.435$ GHz, $f_0 = 2.415$ GHz, and frequency offset $\beta = 250$ KHz. The sampling bandwidth is 1 MHz. We let node SR send a grayscale (128×128)-pixel image and focus on the primary transmission result. In Figure 15, we show the transmitted image from SR and decoded image at D. The received image at D is at low quality (due to the imperfect channel estimation at SR) but observable. This first observation shows that the primary system can still communicate its information while allowing the VFDM-based secondary system access its spectrum. Although the number of faulty pixels in Figure 15b is still high, our result serves as a proof for practical feasibility of NC and VFDM in cognitive radio network.

(a) Transmitted image from SR (b) Decoded image at D

Figure 15. The transmitted (128×128)-pixel and decoded image in the primary tier of the implemented cognitive radio network.

6 CONCLUSIONS

In this paper, we have presented an implementation of OFDM-based NC in three scenarios, namely, a TWR model, a joint source-network coding for multimedia transmission, and a cognitive radio network adopting NC in the secondary tier. Our implementation testbeds operate in real time using the SDR technology. Our results not only complement the theoretical analyses in the literature in showing that NC can improve the network throughput and shorten transmission time, but also confirm the compatibility of NC in practical applications.

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