Partial Network Coding with Cooperation: A Cross-layer Design for Multi-hop Wireless Networks

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***Abstract*—In this paper we propose a partial network coding with cooperation (PNC-COOP) scheme that mitigates error propagation due to channel imperfections and achieves acceptable throughput in wireless ad hoc networks. It combines opportunistic network coding with decode-and-forward cooperative diversity. The proposed PNC-COOP is a decentralized strategy which provides substantial benefits when transmission power is a concern. Simulation of a 16-node wireless mesh network when PNC-COOP is applied to 11-15% of the transmitted packets results in 5 dB BER performance improvement compared to opportunistic network coding. It reduces the average transmitted energy per node by 9-10% as well as the overall average transmitted energy of the network by 3.5%.**

***Keywords*-Opportunistic network coding, decode-and-forward, cooperative diversity, wireless, ad hoc network.**

I. INTRODUCTION

Network Coding (NC), introduced by Alshwede and Yeung [1], has received much attention and has been extensively studied by researchers as an emerging technology to increase the throughput of both wired and wireless networks [2] . However, the technique suffers from practical limitations imposed by the channel, such as signal fading and noise corruption at the receiver front-end [3]. Consequently, the received packet is corrupted. In addition, error propagation also occurs in the network decoding process due to the incorrect packets previously received. Thus, network coding alone may not be sufficient to provide acceptable quality of service, i.e. high transmission rate and low bit error rate (BER) when the channel condition is poor. In this paper, we propose a new technique called partial network coding with cooperation (PNC-COOP). It is a cross-layer design that uses opportunistic network coding [2] at the link layer and decode-and-forward cooperative diversity [4] at the physical layer to improve the reliability of the communication link in a wireless network while maintain relatively high throughput.

Many researchers have made similar attempts to exploit the benefit of network coding and cooperative diversity. The study in [5] is one of the initial works which considered how to obtain diversity in a wireless network with network coding. While this study mainly focuses on the uplink communication with a single destination, the downlink communication is studied in [6]. For wireless ad hoc networks, it is possible to separate the studies into 2 groups; single-hop and multi-hop communications. Single-hop communication studies assume that the source and destination node pairs are in the same coverage area. Each destination is always able to receive data directly from the source node, while additional information of the data may be received from other nodes which overhear the transmitted data. For example, [7] proposes opportunistic network-coded cooperation (ONCC) where the relay node cooperates with sender nodes only when the communication between source and destination node fails. The relay node then forwards a replica of the packets to the destinations. [8] considers the case where each source node cooperates to be a relay node for one another. In addition, [9] applies dirty paper precoding and analog network coding. For multi-hop communication studies, source and destination nodes are not in the same coverage area and cannot transmit or receive data directly to or from each other. Instead, the source node must send data to the destination via intermediate nodes. In [10], a technique called opportunistic cooperative network coding (OCNC) is proposed for a network where multiple intermediate nodes exist between the source and destination node. The technique is applied to each intermediate node by augmenting cooperative diversity and space-time coding with network coding. Assuming the sources are destinations of each other and intermediate nodes communicate with one another, the intermediate nodes seek the opportunity that some may receive both packets from each sender correctly and use the nodes to network code the received packets and broadcast as cooperative packets to both destinations simultaneously. To avoid confusion, it should be pointed out that the previously mentioned studies mainly focused on how to incorporate network coding to reduce the number of transmissions. We, on the other hand, focus on how to mitigate error propagation due to network coding by using a cooperative diversity technique.

Our contribution can be summarized as follows: First, we propose PNC-COOP, a technique applied over multi-hop communications which combines opportunistic NC, opportunistic listening, and opportunistic cooperation together. That is, depending on the quality of the links, each node seeks an opportunity to listen to packets in the vicinity and collect them. Depending on the network traffic and packets in the queue, the node finds an opportunity to perform network coding. Finally, whenever network coding is performed, cooperative diversity is also applied. Second, we design a cross layer scheme between MAC and physical layers for PNC-COOP. Third, we evaluate PNC-COOP using a complex scenario of a wireless ad hoc network with a multi-hop scenario where nodes are connected together randomly. While other techniques often restrict themselves to a particular scenario, PNC-COOP is applied based upon the available opportunity. Thus, the performance evaluation reflects the actual effectiveness of the scheme.

II. PNC-COOP MODEL

A. PNC-COOP principles

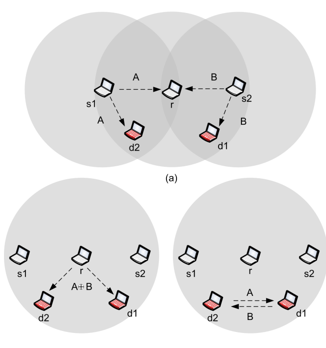

Figure 1. Example of PNC-COOP strategy: (a) Node s1 sends data A to d1 and node s2 sends data B to d2 via node r. (b) Node r overhears and relays A⊕B to d1 and d2. (c) d1 and d2 cooperate to be a partner of one another and forward the data that each needs

Let us define a *direct packet* as the packet transmitted directly from sender to destination node, whereas a *cooperative packet* is the packet forwarded from a relay node in an attempt to provide diversity to the destination node. Thus, cooperative packets are packets decoded and regenerated from direct packets. The principles of PNC-COOP are described as follows: For a sender node with n nodes within its coverage area, PNC-COOP can be applied by selecting k direct packets with different destinations, where $k \geq 1$, and exclusive-OR them together. All k destination nodes must be able to decode the network encoded packet. That is, each of the destination nodes must have $k-1$ packets stored in its temporary buffer. Only this subset of k nodes will join in the cooperation phase by forwarding all $k-1$ packets regenerated from their temporary buffer to one another. Therefore, each destination node will receive $k-1$ cooperative packets. Direct and cooperative packets received at the destination node are then all used for recovering the original packet which the sender intended to transmit. If no network coding can be applied, i.e. $k = 1$, cooperative diversity is not used. If any surrounding nodes other than the destination listen to the encoded packet and are able to decode it successfully, it may also join the scheme to forward additional cooperative packets to the destination. This is left as an option and will not be evaluated in this study. Notice that the strategy is called "partial" due to the fact that only some packets are network encoded and only a subset of nodes in the coverage area of the sender node joins the scheme. Packets that are network encoded together must only come from direct packets waiting in the transmitting queue. Cooperative packets are more likely to cause error propagation since the packets are forwarded from relay nodes. An example of PNC-COOP is shown in Fig. 1 where 2 packets are network encoded ($k = 2$).

The opportunistic listening algorithm used in PNC-COOP is similar to the original method described in [2] with additional criteria. To reduce error propagation, only direct packets with no network coding will be listened to. CRC-CCITT can also be implemented to detect errors. Only packets with no error detected will be kept in soft value form, i.e. the log-likelihood ratio. Otherwise, they are discarded.

The network encoding procedure of PNC-COOP is slightly different from the original scheme which aims to maximize the number of packets encoded together in a single transmission. For PNC-COOP, only a direct packet is used to network encode. A node with transmitting queue containing s direct packets waiting to be transmitted, we select the largest possible k out of s packets, all of which have different destinations, to be encoded such that all destinations can successfully decode the packet. However, in some instances, having a maximum number of packets combined together may cause a higher packet end-to-end delay since the destination may not exist in the coverage area at that particular time. Also, the amount of exhaustive searches for finding the packet combination can grow exponentially when a large number of packets is stored in the queue. Therefore, an additional rule is applied. The first direct packet stored in the transmitting queue is always added to the combination. This additional rule provides a transmitting priority to the encoding scheme which not only reduces the packet delay, but also significantly reduces the combination search space.

B. MAC Protocol

IEEE 802.11 MAC protocol standard with carrier sense multiple access with collision avoidance (CSMA/CA), RTS/CTS, and link-layer acknowledgement are applied in our model. By doing so, each node is allowed to occupy the entire medium without any interference from the others until the transmission is completed. In addition, frequency division or code division multiple access may be applied to the scheme in order to transmit multiple packets at the same time. However, contrary to most multiple access techniques, the node which successfully accesses the medium will occupy all the channels and transmit as many packets as possible through each channel.

C. Transceiver and channel model

Here we consider a frequency division multiplexing communication scheme where the global channel is divided into K frequency bands with center frequencies $f_{c1}, f_{c2}, f_{c3}, ..., f_{ck}$. Assuming M-ary phase shift keying modulation, every $\log_2(M)$-size sequence $\mathbf{x} = [x_0, x_1, ..., x_{\log_2(M-1)}]$ is mapped into a symbol m, where $m = 0, 1, ..., M-1$, and modulated. The received signal of the k^{th} channel then can be written as

$$r_k(t) = \alpha_k \sqrt{\frac{2}{T_s}} \tilde{s}^I_{mk}(t) \cos(2\pi f_{ck} t + \theta_k) - \alpha_k \sqrt{\frac{2}{T_s}} \tilde{s}^Q_{mk}(t) \sin(2\pi f_{ck} t + \theta_k) + z(t), \quad (1)$$

where $\tilde{s}^I_{mk}(t) = \sqrt{E_s} \cos\left(\frac{2\pi m_k}{M}\right)$ and $\tilde{s}^Q_{mk}(t) = \sqrt{E_s} \sin\left(\frac{2\pi m_k}{M}\right)$ are the in phase and quadrature components of the baseband signal. α_k and θ_k are the random fading magnitude and phase of the k^{th} channel. The channel is modeled as a frequency non-selective, slowly fading channel. Since all packets from the same sender are transmitted synchronously on each channel, we can consider that there is no signal interference from other nodes and also between transmitted packets. $z(t)$ is the additive white Gaussian noise with zero mean and autocorrelation $(N_0/2)\delta(\tau)$. Assuming the channel side information is known at the receiver, the k^{th} baseband received signal at the correlator output is $\mathbf{y}^{(k)} = [\ y^{(k)}_1 \quad y^{(k)}_2\ ]$, where

$$\begin{aligned} y^{(k)}_1 &= \alpha_k \tilde{s}^I_{mk} + z^I \\ y^{(k)}_2 &= \alpha_k \tilde{s}^Q_{mk} + z^Q \end{aligned} \quad (2)$$

z^I and z^Q are the noise components output by the correlator which are described by

$$\begin{aligned} z^I &= \int_0^{T_s} z(t) \sqrt{\frac{2}{T_s}} \cos(2\pi f_{ck} t + \theta_k) dt \\ z^Q &= \int_0^{T_s} z(t) \sqrt{\frac{2}{T_s}} \sin(2\pi f_{ck} t + \theta_k) dt \end{aligned} \quad (3)$$

We then can find the log-likelihood ratio of the received signal $\mathbf{y}^{(k)}$ given bit x_i is sent by

$$L(\mathbf{y}^{(k)}|x_i) \cong \frac{1}{N_0} \left(\min_{\tilde{\mathbf{s}}_{mk}: \in S_i^{(-1)}} ||\mathbf{y}^{(k)} - \alpha_k \tilde{\mathbf{s}}_{mk}||^2 - \min_{\tilde{\mathbf{s}}_{mk}: \in S_i^{(+1)}} ||\mathbf{y}^{(k)} - \alpha_k \tilde{\mathbf{s}}_{mk}||^2 \right) \quad (4)$$

Fig. 2 shows the proposed cross-layer design scheme. The link layer controls the handling of all the received packets and the physical layer implements the algorithm used to demodulate and decode the direct packet. When a node receives a packet, it checks whether itself is the destination of the packet or not. If it is the destination, the received packet is then stored in the receiving queue. The node then proceeds to decode after all cooperative packets are received. Though it is not applied in this study, a timer can be used to limit the waiting time.

If the node is not the destination of the packet,

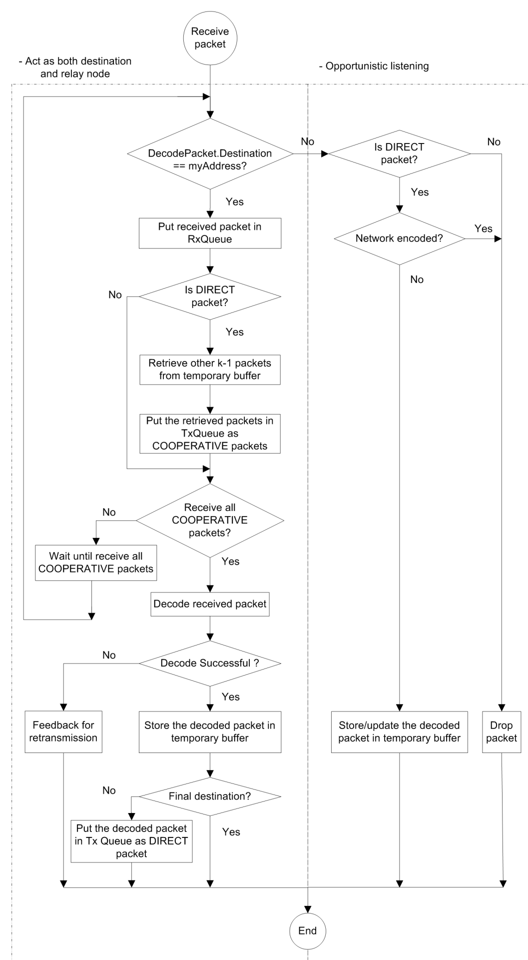

Figure 2. Link layer design for the PNC-COOP receiver

opportunistic listening is used. While the number of nodes forwarding cooperative packets can actually be

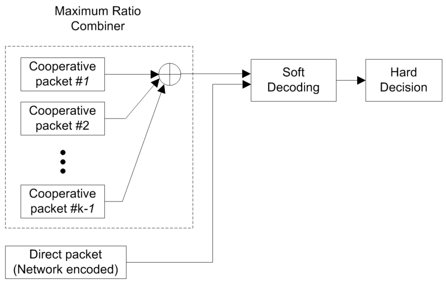

Figure 3. Decoder for PNC-COOP

varied, we present the most basic strategy where the destination nodes of a k network encoded packet must forward other $k-1$ packets contained in the encoded packet to one another. Since a decode and forward cooperative strategy is used, the packets are regenerated from the soft value kept in the temporary buffer by hard decision decoding and added to the transmitting queue.

The proposed decoder operates on both maximum ratio combined cooperative information and network coded data, as shown in Fig. 3. It then outputs soft information, which is input to a hard decision. To avoid confusion, let us slightly change the notation of each bit contained in a packet using $x_{i,k}$ to represent the i^{th} bit of packet k. Suppose it is network encoded with bits $x_{i,1}, x_{i,2}, ..., x_{i,k-1}$ from other $k-1$ packets, i.e., $x_i = x_{i,1} \oplus \hat{x}_{i,2} \oplus ...\hat{x}_{i,k}$, and transmitted as x_i to destination node. The estimate of the transmitted bit $\hat{x}_{i,k}$, given it receives $\mathbf{y}^{(k)}$ from the direct transmission and $k-1$ cooperative bits $\mathbf{y}^{(1)}, ..., \mathbf{y}^{(k-1)}$ from relay nodes, can be given by

$$L(\hat{x}_{i,k}) = L(x_{i,k}|\mathbf{y}^{(k)}) + L\left(x_{i,k}|\mathbf{y}^{(1)}, ..., \mathbf{y}^{(k-1)}\right). \tag{5}$$

Assuming that the a priori value for information bit $x_{i,k}$ is transmitted with equal probability and $\mathbf{y}^{(1)}, ..., \mathbf{y}^{(k-1)}, \mathbf{y}^{(k)}$ are received independently of one another. $L(\hat{x}_{i,k})$ becomes

$$\begin{aligned} L(\hat{x}_{i,k}) =& L(x_i \oplus \hat{x}_{i,1} \oplus \hat{x}_{i,2} \oplus ...\hat{x}_{i,k-1}|\mathbf{y}^{(k)}) \\ &+ \sum_{l=1}^{k-1} L(\mathbf{y}^{(l)}|x_n). \end{aligned} \tag{6}$$

Notice that $x_{i,k} = x_i \oplus \hat{x}_{i,1} \oplus \hat{x}_{i,2} \oplus ...\hat{x}_{i,k-1}$, where bits $\hat{x}_{i,1}, \hat{x}_{i,2}, ..., \hat{x}_{i,k-1}$ are the estimated values of the other $k-1$ packets stored in the temporary buffer of the receiving node. Using similar manipulation provided in [11], $L(\hat{x}_{i,k})$ becomes,

$$\begin{aligned} L(x_{i,k}) =& 2\,\mathrm{arctanh}\Bigg(\tanh\left(\frac{L(x_i|\mathbf{y}^{(k)})}{2}\right) \times \\ & \prod_{j=1}^{k-1} \tanh\left(\frac{L(\hat{x}_{i,j}|\mathbf{y}^{(k)})}{2}\right)\Bigg) + \sum_{l=1}^{k-1} L(\mathbf{y}^{(l)}|x_k). \end{aligned} \tag{7}$$

Since all the $\hat{x}_{i,j}$ terms do not depend on the current received signal $\mathbf{y}^{(k)}$. $L(\hat{x}_{i,j}|\mathbf{y}^{(k)})$ becomes $L(\hat{x}_{i,j})$. After applying Bayes' rule, (7) can be approximated by

$$\begin{aligned} L(\hat{x}_{i,k}) \approx & \left(\mathrm{sign}(L(\mathbf{y}^{(k)}|x_i)) \prod_{j=1}^{k-1} \mathrm{sign}(L(\hat{x}_{i,j}))\right) \times \\ & \min\left(|L(\mathbf{y}^{(k)}|x_i)|, |L(\hat{x}_{i,1})|, ..., |L(\hat{x}_{i,k-1})|\right) \\ & \underbrace{+ \sum_{l=1}^{k-1} L(\mathbf{y}^{(l)}|x_k)}_{\text{Maximal Ratio Combining}}. \end{aligned} \tag{8}$$

For the quadriphase-shift keying (QPSK) carrier modulation case,

$$\begin{aligned} L(\hat{x}_{i,k}) =& \left(\mathrm{sign}\left(\frac{4\alpha_k\sqrt{E_s}y_i^{(k)}}{N_0}\right) \prod_{j=1}^{k-1} \mathrm{sign}(L(\hat{x}_{i,j}))\right) \times \\ & \min\left(\left|\frac{4\alpha_k\sqrt{E_s}y_i^{(k)}}{N_0}\right|, |L(\hat{x}_{i,1})|, ..., |L(\hat{x}_{i,k-1})|\right) \\ & + \frac{4\sqrt{E_s}}{N_0}\sum_{l=1}^{k-1} \alpha_l y_i^{(l)} \end{aligned} \tag{9}$$

Hard decision is now applied, i.e. $L(\hat{x}_n) \geq 0$ implies a logic 0.

III. Performance analysis

A. BER at fixed amount of network coding

In this section, we first evaluate the average end-to-BER of the simplest 2 hops scenario shown in Fig. 1 to justify the benefit of PNC-COOP. The effectiveness of the scheme over a more realistic network scenario will be provided in the next section.

Let us assume a balanced link condition, i.e., all communication links in the network have the same average received bit signal-to-noise ratio. Fig. 4 shows the average end-to-end BER for PNC-COOP, Opportunistic NC and conventional transmission (denoted by Direct Tx). PNC-COOP has the lowest average end-to-end BER compared to the others at the same average received SNR/bit/hop. It requires approximately

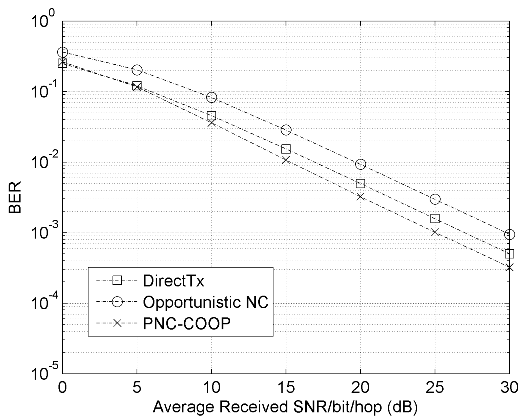

Figure 4. Average end-to-end BER of the network shown in Fig. 1 when the network encode amount k=2

5 and 2 dB less received power than Opportunistic NC and Direct Tx, respectively, to obtain the same BER performance. We also investigate the effect of error propagation in Fig. 5 by considering 2 additional conditions, i.e. when no errors occur in the listened packets and when no errors occur in the packets before network encoding. The average end-to-end BER gets smaller as each condition is applied and the performance of PNC-COOP becomes equivalent to that achieved by maximal ratio combining when both conditions occur, that is, the performance corresponding to diversity of order $k = 2$ is achieved. Similar results are obtained

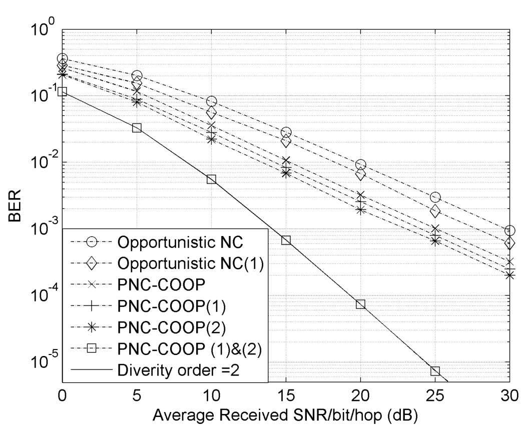

Figure 5. Average end-to-end BER of the network shown in Fig. 1 with different conditions

when the number of network encoded packets is equal to 3 (see Fig. 6). In this scenario, PNC-COOP has a diversity gain of 8 dB over Opportunistic NC and 3 dB over Direct Tx. The end-to-end BER of PNC-COOP converges to diversity of order $k = 3$ when the two previous conditions are met.

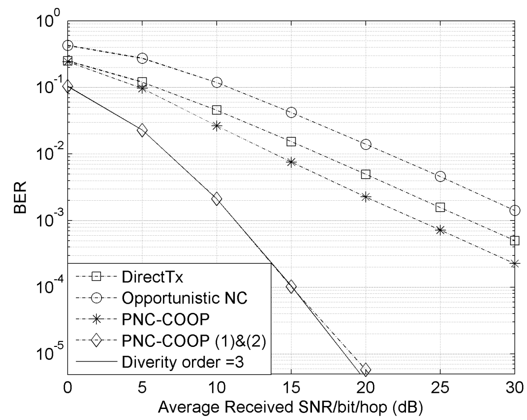

Figure 6. Average end-to-end BER when the network encode amount k=3

B. *Effectiveness of PNC-COOP*

Figs. 5 and 6 show system performance over 2 hops in a specific scenario that ensures network coding will occur with diversity equal to $k = 2$ and 3, respectively. In practice, however, the network topology is random. Hence, the opportunity to network encode k arbitrary packets is also random. For this reason, we simulate communication of a 16-node square-grid wireless mesh network with a 300 meter node separation. Packets of payload size 1024 bytes are uniformly randomly transmitted among the nodes. Large-scale path loss model with shadowing effects [12] is applied to determine received power at each node in the coverage area. By using QPSK at 2.4 GHz with unit gain antennas in the network, the path loss is given by

$$PL(d) = -20\log\left(\frac{1}{32\pi}\right) + 10n\log(d) + X_\sigma \quad (10)$$

X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ (in dB). According to [13], the approximate values of n and σ for an indoor environment are 2.4 and 5.8 dB, respectively. Using the transmitting power and the receiving sensitivity at 100 dBm and -80 dBm, respectively, the coverage area of each node then can be found. This provides a random coverage area for each node. However, for study purposes, it is necessary to fix the number of nodes in the coverage area of each transmitting node, and the number of hops to be the same, in order to maintain the same average amount of network coding through the entire network. The number of hops also affects the BER performance evaluation. Thus the number of hops between the source and destination nodes for every packet transmitted is set to 3 hops and the number of nodes in each coverage area is set to 6. Evaluation of the network throughput is somewhat tricky since the amount

Table I
SIMULATION PARAMETERS

Parameters	Setting
Offered Load	10 Mbps
Bit rate	2 Mbps
CSMA/CA	Use
DIFS	50 μsec
SIFS	10 μsec
RTS/CTS/ACK	1 μsec
aSlotTime	15 μsec
Cyclic Redundancy Check (CRC)	Use

of network coding varies randomly in each transmission. Therefore, for a fair comparison, the number of channels used must also be varied according to the number of network encoded packets. This is not practical for frequency division multiplexing, thus, we fix the number of frequency channels. For simulation purposes, we set the maximum possible number of packets to encode to 6. Other network parameters are summarized in table 1. The average end-to-end BER of the above scenario is shown in Fig. 7. PNC-COOP requires approximately 5 and 2 dB less average received power than Opportunistic NC and Direct Tx, respectively, to achieve the same BER performance. It is observed that the BER is higher than that obtained in Figs. 4 and 6. This is because only a portion of the transmitted packets is network encoded. According to the simulation result shown in table 2, only 11-15% of the packets transmitted in the network are encoded. Also, among these packets, the average number of network encoded packets is around $k = 2$. Despite the lower amount of network encoded packets compared with [2], due to different network assumptions, the trend is similar.

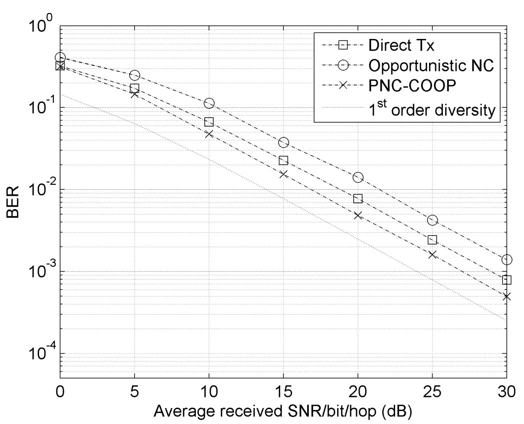

Figure 7. Average end-to-end BER over a 16 nodes wireless ad hoc network using setting described in section III.B

The average network throughput for a range of SNR values is shown in Fig. 8. The throughput of PNC-COOP is approximately 25% less than that of Opportunistic NC. However, we have to keep in mind that the packets received at the destination node when PNC-COOP is used have far fewer errors for the same SNR. PNC-COOP also affords the added benefit of using less energy, on average, to transmit each information bit. We may also eliminate this problem by using code division multiple access instead of the frequency division technique.

Table II
THE AMOUNT OF PACKETS NETWORK ENCODED AT DIFFERENT AVERAGE SNR/BIT/HOP

Method	SNR	Number packets network coded together (%)				Total NC amount (%)
	(dB)	None	2	3	≥ 4	
PNC-COOP	0	96.80	3.19	0.02	0.00	3.20
	5	89.00	10.45	0.54	0.00	11.00
	10	86.19	12.77	1.01	0.03	13.81
	15	85.70	12.81	1.45	0.04	14.30
	20	84.66	14.04	1.28	0.02	15.34
	25	85.25	13.43	1.29	0.04	14.75
	30	86.31	12.14	1.48	0.07	13.69
Opportunistic NC	0	85.45	12.64	1.74	0.17	14.55
	5	86.74	12.28	0.95	0.03	13.26
	10	82.17	16.24	1.56	0.04	17.83
	15	85.27	13.48	1.24	0.02	14.73
	20	83.66	15.03	1.29	0.02	16.34
	25	82.62	15.89	1.42	0.07	17.38
	30	83.91	13.88	2.04	0.16	16.09

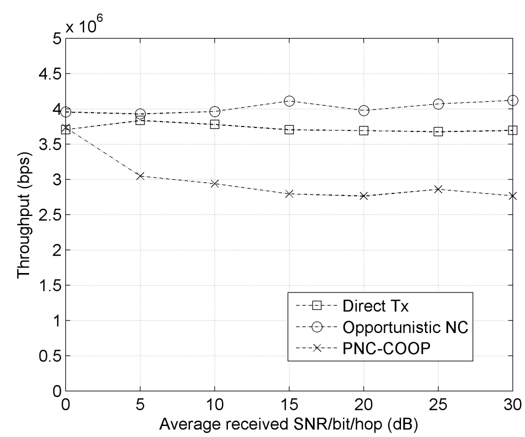

Figure 8. Average network throughput

Although the received energy per bit in all strategies is equal to E_b, the average transmitted energy used per information bit $\bar{E}_b$ is different. Direct Tx and Opportunistic NC use energy equal to E_b to transmit each bit in the packet, while PNC-COOP uses energy equal to E_b/k per bit in all direct and cooperative packets. Moreover, each bit of a k network encoded packet actually contains k information bits. Thus, the average energy used per information bit transmitted can be calculated by

$$\text{Direct transmission: } \bar{E}_b = E_b, \quad (11)$$

$$\text{Opportunistic NC:} \quad \bar{E}_b = \sum_{k=1}^{n} \frac{E_b}{k} P\{K = k\}, \quad (12)$$

$$\text{PNC-COOP: } \bar{E}_b = \sum_{k=1}^{n} E_b \left(1 - \frac{k-1}{k^2}\right) P\{K = k\}. \quad (13)$$

The random variable K is the number of packets network encoded together with probability $P\{K = k\}$, $k = 1, 2, 3, \ldots$. For each transmission, the amount of energy used per information bit is plotted for different values of k in Figs. 9 and 10. Opportunistic NC uses the least amount of energy per information bit. The more packets encoded together, the more energy saving per bit. The PNC-COOP strategy also uses less energy per information bit compared to Direct Tx. The highest energy saving per bit is 25% when $k = 2$. The amount of transmitted energy used per information bit literally increases when k increases since more energy is required for transmitting cooperative packets at cooperative nodes. However, if the sender node is only considered, PNC-COOP uses only $1/k^2$ while Opportunistic NC uses $1/k$ of the transmitted energy per information bit used in Direct Tx. Table 3 shows

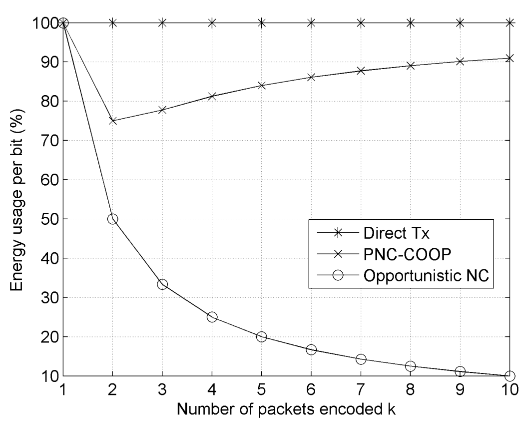

Figure 9. Transmitted energy per information bit for different amounts of network coding

the simulation result of the actual average transmitted energy per information bit in the network using PNC-COOP and Opportunistic NC. Both strategies reduce the amount of energy used in each information bit compared to direct Tx. On average, the sender node in PNC-COOP and Opportunistic NC uses 9-10% and 8-9% less, respectively, than Direct Tx. The overall network energy reduction is around 3.5%.

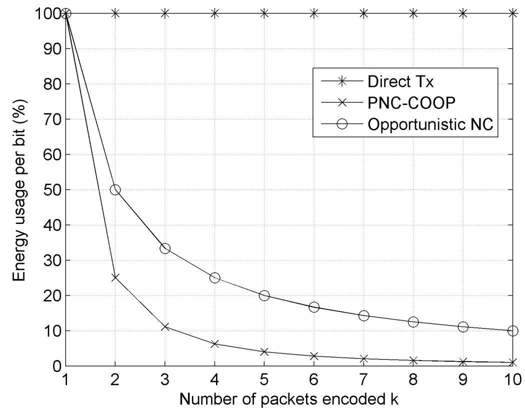

Figure 10. Transmitted energy per information bit at the sender node for different amounts of network coding

Table III
SIMULATION RESULT OF ACTUAL AVERAGE TRANSMITTED ENERGY PER INFORMATION BIT

	SNR (dB)	Avg. Tx energy/bit at sender (%)	Avg. energy saving/bit at sender (%)	Overall avg. energy used per bit (%)	Overall avg. energy saving per bit (%)
PNC-COOP	0	97.60	2.40	99.20	0.80
	5	91.68	8.32	97.27	2.73
	10	89.49	10.51	96.58	3.42
	15	89.06	10.94	96.47	3.53
	20	88.32	11.68	96.20	3.80
	25	88.75	11.25	96.35	3.65
	30	89.51	10.49	96.62	3.38
Opportunistic NC	0	92.39	7.61	92.39	7.61
	5	93.20	6.80	93.20	6.80
	10	90.82	9.18	90.82	9.18
	15	92.42	7.58	92.42	7.58
	20	91.61	8.39	91.61	8.39
	25	91.06	8.94	91.06	8.94
	30	91.58	8.42	91.58	8.42

C. Factors that affect performance of PNC-COOP

A couple of factors have been observed in the simulation that affect the performance of PNC-COOP. First, the number of hops and nodes in the coverage area are crucial. The larger the number of hops and nodes in the coverage area, the more packets the nodes can listen to. Thus, the sender node is able to encode more packets. Second, the number of packets remaining in the transmitting queue dictates the amount of candidate packets that the sender node could possibly combine. When few packets remain in the transmitting queue, the chance to combine packets that the receiving nodes can decode is very low. Third, it is important to keep only low BER packets from opportunistic listening packets. Packets in poor condition cause more errors to propagate in both the decoding process and relaying phase. These factors would affect the network performance when deploying either opportunistic NC or PNC-COOP.

IV. Conclusion

In this paper we have presented the new PNC-COOP strategy for wireless communications in ad hoc networks. It was shown via simulation that the scheme not only reduces the bit errors caused by channel imperfections, but also provides a decentralized energy-efficient distributed method among network nodes. When using this technique, the source node consumes, on average, less energy per transmitted information bit. Even though a reduction in throughput occurs, the quality of the received data at the destination node is far superior than that achieved by other strategies. The effectiveness of the scheme clearly depends on the opportunity to perform network coding and the quality of the listened and encoded packets.

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