Chapter 43
The Techniques of Network Coding Applied in the Physical-Layer of the Wireless Communication Systems: A Survey

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43.1 Introduction

Network coding [1, 2] is an innovative multicast transmission technique which allows a node to encode its received data before passing it on. Different from the traditional storage-and-forward way, the intermediate routing nodes encode the data and then forward. Through the encoding scheme the data rate of each node can achieve the max-flow bound. The original intention of the network coding technique is to improve the system transmission data rate or the network throughput. But furthermore, the advantages extend to intensify the network robust ability, promote the system security and save the energy consumption.

This survey focuses on discussing the techniques of network coding applied in the physical-layer of the wireless communication systems for two domains: the PNC and the joint design of the network and the channel coding. Firstly, the main research contents and directions of PNC are concluded on the basis of analyzing the PNC mechanism and studying the current situation and the developing trend. Then, different designs of the network and channel coding are categorized and summed up.

43.2 Network Coding Applications

Figure 43.1, which is commonly known as the butterfly network, depicts a communication network where two data bits b_1 and b_2 are multicast from the source node S to both the nodes R_1 and R_2. The vertices correspond to terminals and the edges correspond to channels. The data rate of each channel is assumed to 1 bit per time unit. According to the max-flow min-cut theorem of the network information

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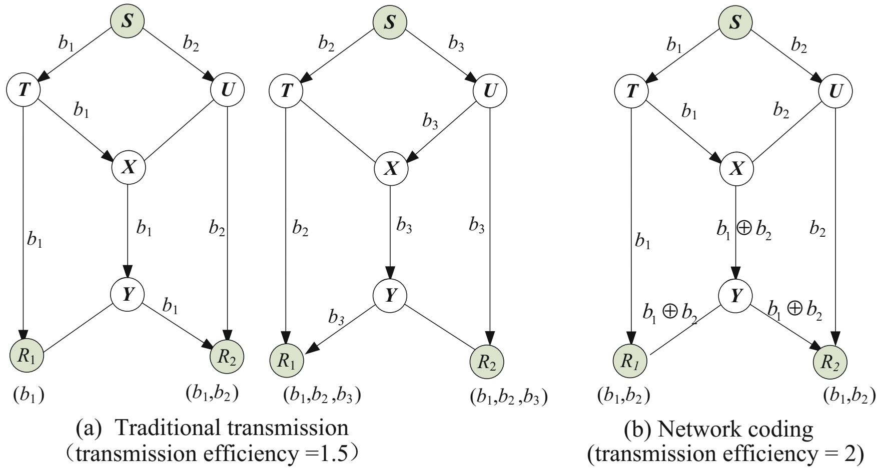

Fig. 43.1 Network coding in the butterfly network

theory, the maximum information rate we can send from S to R_1 and R_2 is equal to the min-cut value, that is, 2 bits per time unit. In the traditional network transmission, as the Fig. 43.1a depicted, S sends b_1, b_2 and b_3 (3 bits) to R_1 and R_2 in 2 time units. This achieves a transmission efficiency equals 1.5. The channel XY, which has unit capacity, becomes the bottleneck of the butterfly network where the intermediate node X has to transmit one bit per time unit. While using network coding, as the Fig. 43.1b depicted, the node X derives from the received bits b_1 and b_2 the exclusive-OR bit $b_1 \oplus b_2$ and then sends it. Through the replicated transmission of node Y, the nodes R_1 receives b_1 and $b_1 \oplus b_2$, from which the bit b_2 can be decoded. Similarly, the node R_2 decodes the bit b_1 from the received bits b_2 and $b_1 \oplus b_2$. As we can see, it achieves transmission efficiency equals 2. Actually, by applying the network coding, the capacity of the network reaches the maximum flow limit while it cannot be accomplished where the intermediate nodes perform just bit replication.

Network coding is an important breakthrough in the information transmission domain. It stems from the wired network and now focuses more on the wireless network. The wireless channel is characteristic as time varying and the downlink transmission is a multicast model, both of which make the network coding technique be prone to combine with the wireless communication. As the Fig. 43.2 shows, the application techniques of network coding in the wireless communication systems can be divided roughly depending on the scenario, the layer and the goal of the applications.

The objectives of the network coding applications are different depending on the scenario and structure of the network. Generally, the wireless communication network can be divided into the single-hop and the multiple-hop networks. In the traditional cellular mobile network and the cognitive radio network which belong to

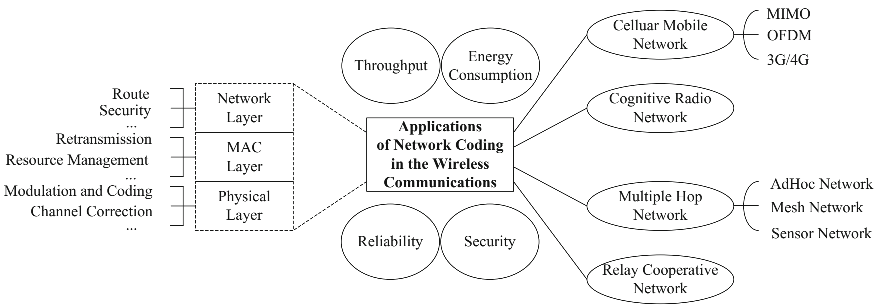

Fig. 43.2 The diagram of applications of network coding in the wireless communication systems

the single hop networks, the objectives of the network coding applications are to improve the system throughput, enhance the transmission reliability and strengthen the system security. While in the wireless Ad Hoc network, the wireless mesh network and the wireless sensor network which belong to the multiple-hop networks, the objectives of the network coding applications are highlighted on reducing energy consumption of the nodes and enhancing the transmission reliability. The relay cooperative network which also belongs to the multiple-hop networks recently become the research hotspot of the network coding application in wireless communication systems. But it is usually combined with the cellular mobile network and the scenarios of which are different from the mesh network. So the application objectives are also throughput, reliability and security.

There are diverse development directions for the network coding applications in each layer of the wireless communication network. In the physical layer, the network coding technique is combined with various transmission techniques such as modulation and coding, channel error correction, multiple input multiple output (MIMO) technique and etc. Specially, the physical-layer network coding (PNC) is an important network coding application technique in the physical layer, based on which lots of technique combinations spring up. In the media access control (MAC) layer, the network coding is more likely to combine with the retransmission, the scheduling, the resource management and etc. In the network layer, in which the network coding presents firstly, the combination is with routing techniques naturally and on the other fact the secure network coding is a newly developing research content.

43.3 Physical-Layer Network Coding (PNC)

43.3.1 The PNC Scheme

PNC technique was firstly proposed by Zhang S. and etc. in 2006 [3]. The main idea of PNC is directly superposing the electromagnetic (EM) wave signals in the physical layer of a relay node through a designed proper

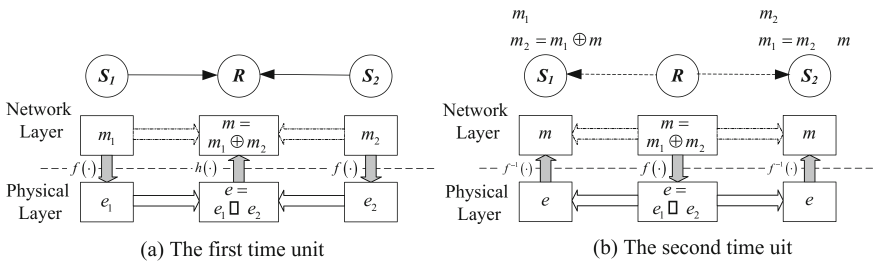

Fig. 43.3 The PNC scheme

modulation-and-demodulation mechanism. The superposition of EM wave signals can be mapped to digital bit streams in GF(2^n), which seem equally as the XOR operation in traditional network coding.

Taking QPSK modulation for example, it can be considered as two BPSK data streams: an in-phase stream and a quadrature-phase stream. We can handle with the two streams in the same way. As depicted in the Fig. 43.3, a three node two-way transmission linear network scenario is considered, m_i denotes the bit data sent by two source nodes S_1 and S_2. After the corresponding modulation, the value domain of the electromagnetic wave signals is $e_i \in \{-1, 1\}$. The modulation mapping function is $f(\cdot) : e_i = 2m_i - 1$ for QPSK modulation and the EM wave signal is transmitted through the physical layer of each source node. Assuming symbol-level and carrier phase synchronization, the physical layer of the relay node receives the superposition of the EM wave from two source nodes and the amplitude value domain is $(e_1 + e_2) \in \{-2, 0, 2\}$. A many-to-one mapping function $h(\cdot)$ can be designed in order to map the superposition EM wave signals in the physical node to the bit data value in the network layer of the relay node. Making the values of the function equal to the XOR values of the bit data if applying network coding directly, thus the scheme actually realizes the network coding in the physical layer.

For QPSK modulation, if $m_1 \neq m_2$, thus $m = m_1 \oplus m_2 = -1$, and if $m_1 = m_2$, thus $m = m_1 \oplus m_2 = 1$. As a result, the mapping function $h(\cdot)$ can be designed as follows,

$$m = \begin{cases} -1, e_i = 0 \\ 1, e_i = -2, 2 \end{cases} \tag{43.1}$$

The relay node modulates and transmits the mapped bit data, then the nodes S_1 and S_2 receive and demodulate thus both can get coded bit data $m = m_1 \oplus m_2$. According to the signal m_1 and m_2 already known, through the XOR operation, i.e. $m_2 = m_1 \oplus m$ and $m_1 = m_2 \oplus m$, S_1 and S_2 ultimately get mutual information.

Through processing the signal superposition in the physical layer directly, a two-way relay transmission only needs 2 time units using PNC. Compared with 4 time units in the traditional relay system and 3 time units in the traditional network coding system, PNC can yield a 2-time and 1.5-time throughput improvement respectively.

43.3.2 The Research Directions

The PNC combines the coding in the network with the physical layer techniques, such as the modulation mapping and the antenna selection. In utilizing of the wireless channel characteristics, it is more likely to improve the system throughput and enhance the system robustness. The paper [4] analyzes the problems that have to be considered in applying the network coding in the real communication system, including the noise, the synchronization, the channel fading and etc., which are of course the key research contents of the PNC. Only these problems are solved that could the PNC theory step forward to application [5]. Besides, the theoretical researches are still the hot topics as the guide of this innovative conception in the transmission techniques. The research contents are mostly focused on the following aspects.

1. The coding and decoding design

As the PNC scheme shows, the coding and decoding process of PNC is actually the mapping process. For certain modulation mode and given the mapping function $f(\cdot)$, a mapping function $h(\cdot)$ has to be found in order to demodulate the superposed physical signal to get the network coding form of the bit data. The coding and decoding design of PNC lies in the design of the mapping function pair $(f \cdot h)$. The merits of the functions decide the performance of the PNC scheme. The PNC schemes can be categorized as the physical network coding in finite field (PNCF) and in infinite field (PNCI) according to the value domain of the network coding function. Firstly, the PNCF was analyzed assumed in AWGN channel and QPSK modulation. Thereafter more complex modulation modes and channel conditions such as FSK, MPSK and QAM [6–8] in the Rayleigh channel, Nakagami channel and etc. [9, 10] are considered. The representative technique of PNCI is analog network coding (ANC) [11] which outputs analog signal through function mapping. Instead of requiring strict synchronization, it accepts the signal collision interference and makes use of the asynchronization to improve the system throughput. But compared with PNCF, PNCI also amplifies the additive noise in the relay node hence the system performance will deteriorate if the uplink channel conditions grow bad.

2. The synchronization problem

The PNC is presented based on the assumption of fully transmission synchronization at first. However, there exists symbol asynchronization, phase asychronization and etc. and certainly will impact the on the PNC performance. Many researches follow up to analyze how much the effect will be and propose various PNC schemes to cope with the asychronization [12–15]. The study of paper [12] and [13] show that the performance loss of the carrier phase shift, the carrier frequency shift and the symbol shift is <3, <0.6 and <2.2 dB respectively. The paper [16] presents the simulation results in QPSK modulation mode which show that the loss will arrive at 6–7 dB at 10^{-2} bit error rate, in the condition that the phase difference equals $\pi/4$ while the symbols are fully synchronized. But the paper [4] believes that the loss is only about 1 dB if considering the symbol shift. It is on account of the diversity and the transmission certainty effect because of which the symbol shift on the contrary compensates on the loss produced by the phase shift. It demonstrates that in actual system the transmission performance may not deteriorate so much owing to the asychronization as in the limiting case. In spite, it needs further step research that how much of symbol shift could decrease the loss of the performance. Besides, the channel estimation in the PNC is also a research direction [17, 18].

3. The combination with other transmission techniques

PNC realizes the networking coding technique in the physical layer, thus naturally could combine with the transmission techniques of the physical layer to exploit the function of the network coding. The joint design of PNC and channel coding is an aspect more researches focus on [19–21]. Besides, PNC is combined with MIMO-OFDM. The asynchronized PNC can be constructed utilizing the advantages of OFDM and multiple antennas [22, 23]. It is worth to mention that PNC could combine with secure transmission techniques. By making use of the physical layer characteristics of the wireless channel (such as the fading, the noise and etc.), the quality of the main channel need to be guaranteed better than that of the wiretap channel so that the eavesdropper is unable to acquire any useful information. It integrates the physical layer characteristics, the secure transmission and the network coding effectively and becomes an innovative research direction [24, 25].

4. The PNC capacity

The information theory study of PNC is aiming at deducing the channel capacity of the two-way relay channel, i.e. the maximal information data rate of the two source nodes in the AWGN channel condition. The capacity of the TWRC is seemed as a bound and the capacity of different PNC scheme is compared with that, such as the PNC capacity with channel coding, multiple antennas [26, 27], or with ANC [11, 27]. Specially, because the PNC technique is used for security transmission as well, there comes up the theory researches from the angle of improving the security capacity [28, 29].

5. The application scenario extensions

The two-way relay channel is the main application scenario in the PNC researches. Moreover, the scenarios with multiple users, multiple relays and multiple hops are becoming important contents of PNC researches [30, 31].

43.4 Joint Design of the Network Coding and the Channel Coding

In the wireless network, the most popular scenario of the network coding application is the relay system owing to the mechanism of the network coding. Uniting the relay node taking decode and forward mode with the network coding, obviously could increase the diversity gain and the capacity. And on the other hand, the combination of network coding and channel coding is considered. The redundant information of the relay node which passes on to the destination node can give better error protection and effectively fight against the influence of fading and noise in the channel and hence improve the system reliability.

There are two kinds of methods to combine the network coding and the channel coding. One is the simple combination where each technique is independent. The paper [32] proves that when the channel is discrete memory less and independent in the single source direction network, the separation theorem of the network coding and the channel coding is to be true. The network coding helps reaching the maximal flow bound and the channel coding guarantees the transmission reliability of every link. Considering the complexity of the system and the convenience of the application, the two techniques could be designed separately. As the Fig. 43.4 shows, the flow is as follows:

1. In the source nodes, broadcast the information S_1 and S_2 to the relay node and the base station through channel coding and modulation;
2. In the relay node, get the estimations $\bar{S}_1$ and $\bar{S}_2$ of the source data through demodulation and channel decoding, XOR the estimated data to realize network coding, process the channel coding and modulation again, send them to the base station;
3. In the base station, demodulate and channel decoding the three way data from the two source nodes and the relay node, process the network decoding later, get the final estimations of the data $\hat{S}_1$ and $\hat{S}_2$.

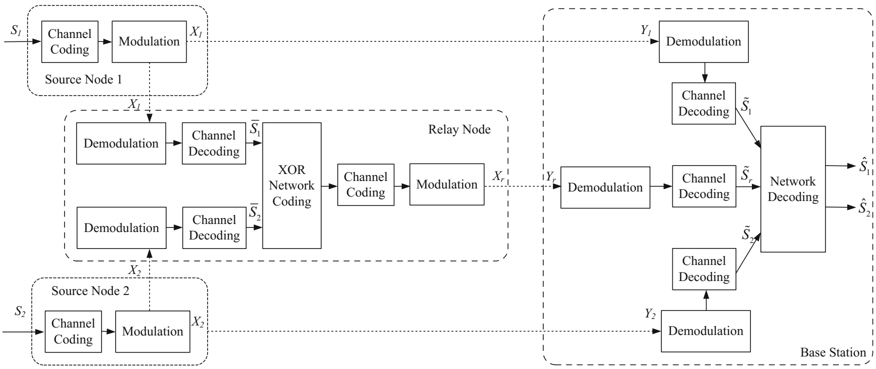

Fig. 43.4 The simple combination of the network coding and the channel coding

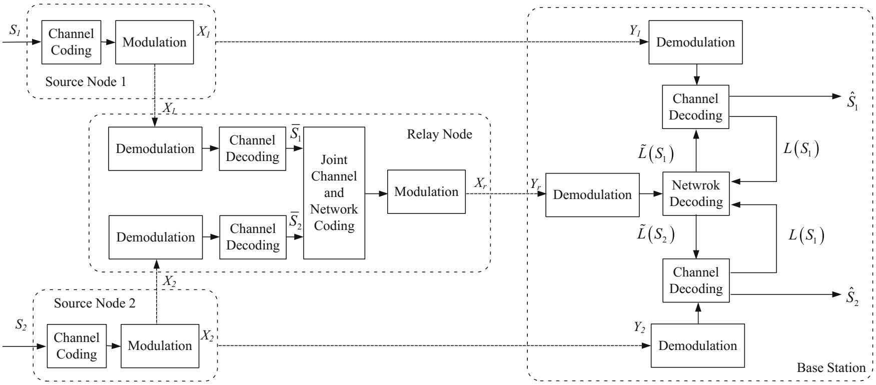

Fig. 43.5 The joint design of the network coding and the channel coding

The other combination method of the network coding and the channel coding is joint design codec. The paper [33] points out that adopting joint coding could get better transmission reliability than separate coding in certain multi-user channel. As the Fig. 43.5 shows, the flow is as follows:

1. In the source nodes, broadcast the information S_1 and S_2 to the relay node and the base station through channel coding and modulation;
2. In the relay node, get the estimations $\bar{S}_1$ and $\bar{S}_2$ of the source data through demodulation and channel decoding, process the channel coding and modulation according to the designed joint network-channel coding scheme which takes the channel coding features into account, send them to the base station;
3. In the base station, receive the data from the two source nodes and the relay node. As the data sent by the relay node is after the joint network-channel coding, there exists parity information of the two source data to assist decoding and the soft information $\tilde{L}(S_1)$ and $\tilde{L}(S_2)$ can be got. The soft information will go into a new round channel decoding process and after several iterations the two channel decoders give hard decisions, thus the final estimations of the data $\hat{S}_1$ and $\hat{S}_2$ will be obtained.

As the researches of the network coding going deeper, the combination of which with the channel coding generally are from the joint design thought. Depending on different angle of the design, the joint designs can be divided into the following categories.

1. Based on the type of the channel coding

The Turbo code and the LDPC code have outstanding error control performance that could nearly approach the Shannon limit bound. The researches focus on techniques based on these two types and so as the network coding. For the Turbo code, the relay node unites the Turbo code and XOR network coding and sends the parity information. The base station makes the joint iterative decoding. For the

LDPC code, the coding principles are usually exploited such as the product code, the Tanner graph and etc. Joint coding and decoding schemes can be realized considering different generator matrix design of the source node information to institute of XOR network coding and optimizing the corresponding LDPC code [34–37].

2. Modify the mode of handling the soft information

The hard decision error of the relay node will lead to whole system performances decrease, so we can use the soft information to design the codec algorithm from the angle of enhancing the signal strength. The relay node does not do the hard decision and instead transmits the soft information after the network coding [38]. If the system complexity is considered, the relay node could still adopt hard decision while adding certain compensation in the soft information of the base station to help the channel and network decoding [39].

3. Utilizing of PNC

The PNC is able to realize network coding through the signal superposition and basing on different modulation and mapping modes. It makes the bit operation on the network layer come true on the physical layer, so the channel coding as an important physical layer technique is apt to jointly design with it. The relay node does not need to do coding and decoding thus can simplify the system complexity greatly and raise the transmission efficiency at the same time [19–21].

4. Considering various system scenarios

For the joint design, the system scenario of two source and single relay is gradually turned into that of multiple relays and multiple user accesses.

Compared with the simple combination design in connecting separated part, the joint network and channel coding starts from the channel coding principles and utilizes the soft information process. Taking the advantages of the PNC, it can acquire improvement on the aspects of the transmission efficiency and the system reliability. Moreover, the joint design shows large superiority on error rate performance especially in good signal to noise conditions.

43.5 Conclusion

The survey studies the application techniques of the network coding in the physical layer of the wireless communication systems. It aims at the hot topics: PNC and the joint design of the network and channel coding, in which the technique application schemes are discussed and the developing directions are presented on the basis of analyzing the technique principles. The researches of the network coding technique are spreading from the physical layer, the MAC layer and the network layer. All kinds of advanced techniques can be combined with it. And the consistent goal is promoting the transition from the theory study to the practical use.

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