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A Survey of Wireless Network Coding

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Abstract: Network coding (NC) over wireless networks has grown in recent years, so there is more attention from research community. NC is a technique that able to enhance the reliability and efficiency of network communications systems. Network coding has the capability to enable the intermediate nodes to combine and send out the received packets previously. NC has two main advantages: improvements in robustness and throughput. In this paper, a literature survey of network coding in a wireless environment is presented. We started by discussing the fundamental characteristics, advantage and disadvantage of network coding. Then we summarized the types of network coding and presented a literature review of network coding applications with routing protocol, throughput and delay modeling, MAC protocol and cross layer design.

Keyword: Network coding, wireless network coding, throughput/delay modeling, routing/MAC protocols, cross layer design.

1. Introduction

Network coding, considered as a transmission paradigm that provides strength in optimizing network resources. It enables better resource utilization and can achieve max-flow, which is the theoretical upper bound of network resource utilization, by allowing a network node such as a router to encode its received data before forwarding it. Network coding is considered as a generalization of conventional store-and-forward routing techniques. Contrarily, traditional coding techniques are referred to as source-based coding, where only source nodes encode packets [1]. In this case, each node was implemented with network coding function instead of simply forward the packets of information to the destination, the nodes of a network will take several packets and encode them together into a single coded packet before forwarding. This can be used to achieve maximum possible information flow in a network. Network coding is a field of information theory and coding theory. Recent researches have proven that network coding has great potential to improve network throughput, reduce delay, and improve robustness in multi-hop wireless networks by exploiting the intrinsic broadcast nature of wireless communication and the native physical-layer coding ability by mixing simultaneously arriving radio waves at relay nodes [1], [2].

In addition, network coding can improve the performance of multicast and achieve maximum multicast capacity by performing encoding operations at intermediate nodes. Network coding allows intermediate nodes in networks to encode several received packets into a single coded packet before forwarding. Contrarily, traditional coding techniques is referred to as source-based coding, where only source nodes encode packets [3], [4]. It is especially suited for new emerging networks such as wireless mesh and sensor networks [5]. However, the problem that has been identified is to compute maximum multicast throughput possible for communication between a source node and a set of receivers [6]. Two steps should be realized when using network coding in multicast communication; the first one is to find correct transmission paths from source to multi-receivers and the second is to determine the coding scheme. Network coding was first introduced by R. Ahlswede et al. [1], which showed that having the routers mix information in different messages allow the communication to achieve multicast capacity. Adequate linear codes to achieve the maximum capacity bounds for multicast traffic were verified [2], [7].

2. Background

Network coding promises to offer benefits along with various dimensions of communication networks such as; throughput, wireless resources, security, complexity, and flexibility to link failures. Here, we will give the summary of benefits of network coding as follows:

- Improve the performance of networks and better exploiting available wireless resources utilization (battery life, wireless bandwidth, and delay).
- Network coding can be used to maintain connections after permanent failures due to a link cut, or the permanent removal of an edge, or other disconnection [8].
- Network coding could be a helpful tool in network management and network robustness.
- Solve the broadcast storm problem for wireless networks by reducing the number of forwarded packets through encoding multiple packets to forward into a single coded packet.
- Throughput maximization through transmission of multiple messages in the same channel.
- Energy minimization and improved routing performance.
- Load balancing and save bandwidth consumption.
- Security against attacks.

On the other hand, there are some disadvantages and drawbacks of network coding, such as [9, 10]:

- Packet latency, an intermediate node needs to wait for a short time to receive other packets from other nodes to combine the packets.
- Large memory requirement, nodes need to store packets instead of immediately broadcasting it.
- High decode complexity of random code.
- Loss some packet, the loss of one packet is the major problem with network coding, for example, if one packet is lost, it could affect the decoding of a number of the original packets and render some useless information at the receiver.

3. Types of Network Coding

The broadcast feature of wireless networks makes them as good candidates for the application of network coding. Other neighbors will hear information that is transmitted when a node transmits a piece of information to one of its neighbors. Therefore, a node of interest to the neighbors for different pieces can transmit an encoded version of all that he had, which would bring benefits to all the neighbors and save wireless resources [11, 12].

In general, there are two categories of network coding: intra-session coding and inter-session coding. In the intra-session coding, nodes can code packets together only if they belong to the same flow (same session), such as MORE [13]. In the inter-session coding, nodes can combine packets from different flows (different sessions) whenever a coding opportunity arises, such as COPE [14].

Fig. 1 explains the network coding work. It showed the standard 3-node relay network, if node A wishes to send a packet to node C and vice versa, this can be done by different ways with varying time allocations. There are different methods in place that restrict the interference between PA and PC and thus increase data accuracy. In addition to these methods, there are those that mix the signal at B either at the bit level or at the analog level (physical layer) [12].

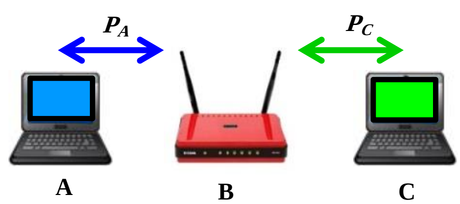


Figure 1: Standard 3-node relay network

One of the unique and critical to these methods is the number of transmission time slots required to complete the transmissions successfully. An important feature of the wireless channel is that, the signals received at the relay are not in bits, but as actual sinusoids. The sinusoids signals are subjected to the effects of noise in the channel before the reception. It is only after deciding the bits and thus data can be pulled from the signals. Analog Network Coding (ANC) [13] takes advantage of the mixing properties of the wireless signals and uses it in increasing the throughput gained in the channel. Three main methods are highlighted in [13], [14], which are used in successful data transmission in this type of network. These methods fall under a category of communications known as Network Coding [15].

3.1 Standard Transmission

In traditional networks as shown in Figure 2, the interference is usually avoided by preventing the overlapping of signals from A and C to B in the same time slot. Standard transmission in the 3-node relay network is simple and done in the following manner. A sends PA to B, which followed by sending PA to C. After this, C sends Pc to B that relays PC to A. The exchange of packets in this type of transmission is a 4-step process. This guarantees no interference between PA and PC and allows the relay to simply amplify (when necessary) the received signal to the other senders without performing any type of decoding.

The decoding of the data from the analog signal is done on A's and C's end. This method of transmission is depicted in Figure 2. Since throughput, gains are desired in wireless channels, a method of transmission in this network that reduces the amount of time slots to complete the data exchange from 4 to something lower, would be beneficial.

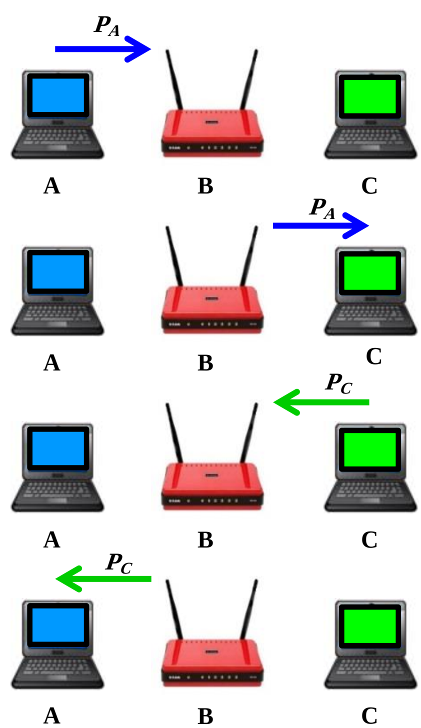


Figure 2: Standard relays transmission

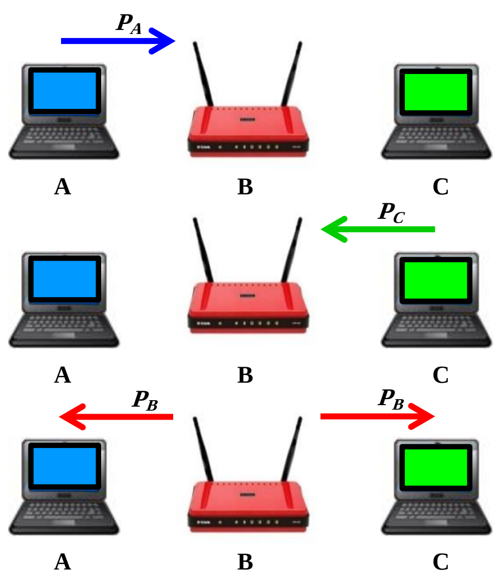
3.2 Digital Network Coding

The second method is Digital Network Coding (DNC). DNC is a method of transmission that performs decoding at the relay. After decoding, the relay broadcasts a signal back to the A and C. In DNC, A sends PA to B and held at the relay. C proceeds by sending PC to B. B then demodulates both signals that it received and performs an XOR on them to produce its own packet PB. After this, B broadcasts the PB back to the senders. This method is done in 3 time slots as opposed to the 4 that it takes in standard transmission. This method utilizes the broadcast property of the wireless channel that allows signals to be passed to multiple receivers at once. Since A and C know the packets that they sent, they can decode PC and PA respectively from the signal B. This method of transmission is depicted in Figure 3. This method of transmission works logically and can be applied in the wireless channel as well.

3.3 Analog Network Coding

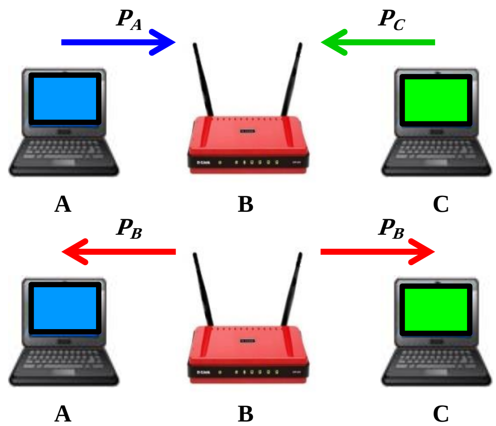
DNC utilizes broadcast feature of the wireless channel and performs XOR operations at the bit level. Wireless interference in the 3-node network is something that is typically avoided, especially in the 802.11 channel, but is exploited by the ANC when the signals from the packets of the two senders collide [13].

In the 802.11 network, different Time Division Multiple Access (TDMA) schemes are utilized to ensure that only one transmission occurs during any time instant. In the ANC, A and C transmit the packets simultaneously to B, which receives the combined signal (PA ⊕ PC). B then forwards, through broadcasting, the mixed signal back to A and C. Figure 4 shows how the transmission is done in this method without noise being factored in C.



$P_B = P_A \oplus P_C$

Figure 3: Digital network coding relay transmission



$$P_B = P_A \oplus P_C$$

Figure 4: Analog network coding relay transmission

It should be noted that the complete transference of the packets PA and PC is done in 2 time slots which delivers a throughput gain of 1.5 over DNC [13].

This method is useful in that the relay does not have to perform any decoding while it is necessary when the DNC is utilized. The relay simply amplifies and forwards the mixed signal.

Another example of network coding is the butterfly network in Figure 5 (a) and (b), a network consisting of source nodes, destination nodes and intermediate nodes.

Each source node wants to distribute its own message to a set of destination nodes with the help of intermediate nodes. As we mentioned earlier, in traditional communication networks, information sent from a source node to a destination node is conveyed through a series of intermediate nodes in the network by store-and-forward switching.

This method has been the dominant technique for sending data over a network, in which relay nodes decode the received data and merely forward these to the next node without modifying the contents of the original data. Due to its broad range of potential applications, network coding has received increasing research interest in information theory, networking and many other fields. In contrast to store-and-forward approaches where the function at an intermediate node is restricted to that of a switch, the key idea of network coding is to allow an intermediate node to mix and process information from multiple links. In this way, the amount of information transmitted through the network can be reduced and hence the network throughput can be increased.

In Figure 5, a source node S wants to transfer two bits P1 and P2 to both receivers R1 and R2 through the network. Each link in the network is assumed to be error free with unit capacity. When store-and-forward is used, each intermediate node replicates what it receives and then forwards it to neighboring nodes. With store-and-forward switching, the network throughput of the butterfly network is dictated by the bottleneck node C.

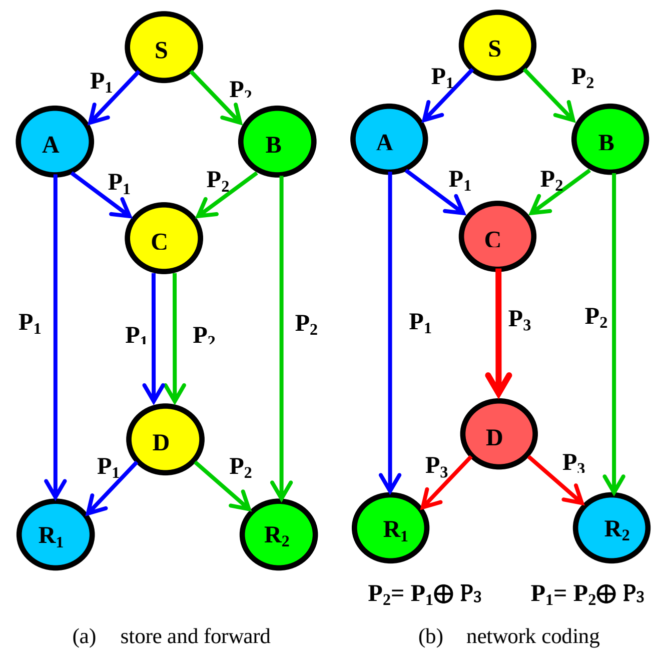


Figure 5: Example for network coding (Butterfly network)

Since the capacity of the link between C and D is one, the node C transmits one bit at a time. In this way, 10 transmissions are required to complete the data transfer. However, when network coding is applied, the bottleneck node C can mix with the incoming data P1 and P2 and compute the exclusive-or (XOR) of both. Since R1 (R2) knows both P1 (P2) and P2 (P1), it can also figure out P2 (P1) by taking the XOR of P1 (P2) and P2 (P1). With network coding, only 9 transmissions are needed, hence we can save bandwidth and energy. For multicast problems in lossless wired networks, it has been shown that the max-flow min-cut upper bound can be achieved with network coding while it is not possible with traditional store-and-forward technique [1].

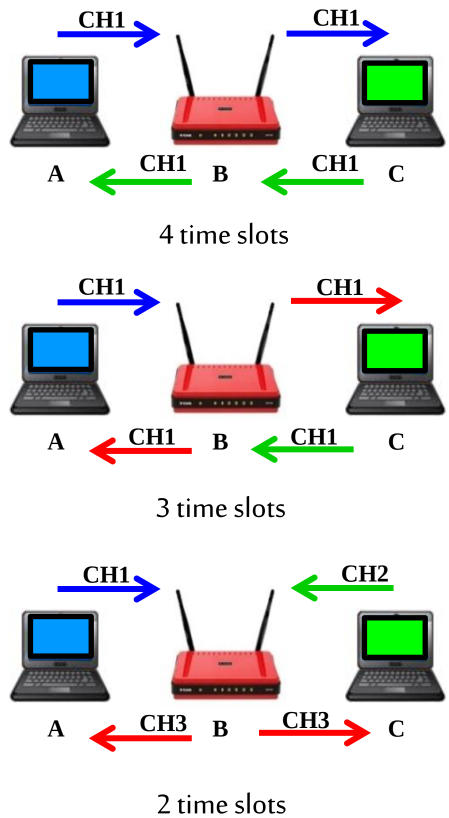


Figure 6: (a) Traditional unicast, (b) Network coding, (c) Network coding in MRMC

Another example that demonstrates the benefits of network coding in multi-channel multi-interface wireless mesh networks is displayed in Figure 6, where, node A and C intend to exchange packets with each other through a shared intermediate forwarder node B. With traditional routing, 4 time slots are needed to finish the packet exchange. Using XOR network coding, 3 slots are needed. When applying network coding in MC-WMN, however, the amortized transmission time is only one slot since the transmission of new packets from A and C can overlap with the broadcasting of previously encoded packets. Although it is possible to achieve the same performance by assigning orthogonal channels to all 4 links, this would require node B to be equipped with 4 interfaces, while network coding only needs 3 interfaces.

3.4 Physical layer network coding

All data at the physical layer of wireless networks are transmitted through electromagnetic waves [15], [16]. The broadcast nature of wireless links is one of the characteristic of wireless communications, which is not found in wired networks. Normally, in wireless communications, the transmission of the electromagnetic waves signals from one source are received by more than one node which are located in the same transmission range. Thus, a receiver node may be receiving the electromagnetic waves signals (data) transmitted by multiple nodes simultaneously at the same time [14]. This advantage is addressed more as an interference-inducing inconvenience in the wireless networks. The physical layer network coding (PLNC) mechanism takes advantage of the broadcast nature of wireless signals by permitting two nodes to transmit simultaneously to the relay node. PLNC technique has several performance advantages, such as improving the throughput and capacity of wireless communications channels and reducing delays. The PLNC technique can fulfill approximately 100% throughput improvement in physical-layer over the multi-hop traditional transmission system and 50% over the straightforward network-coding scheme.

4. Related Work

This section provides a review of the previous works on network coding with computer network application. Next subsections show deeply the previous works of network coding with routing protocol, throughput and delay modelling, MAC protocol and cross layer design.

The summarization of the taxonomy of wireless network coding application researches is presented in Table 1. We classify wireless network coding application research into five sections; routing protocol, throughput modeling and analysis, delay modeling and analysis, MAC protocol and cross layer design and optimization.

4.1 Routing with Network Coding

H. L. Nguyen and U. T. Nguyen [3] proposed a multicast routing algorithm for multi-channel multi-radio (MCMR) WMN. The authors take into account the wireless broadcast advantage and the channel diversity in order to minimize the amount of network bandwidth, consumed by a routing tree in a multi-channel multi-radio (MCMR) wireless mesh network (WMN). The problem of building multicast routing trees with minimum numbers of transmissions in WMNs where multiple channels and multiple radios are studied. The results obtained showed that MCMNTs perform significantly better than commonly used trees such as SPTs, MSTs and MFTs in terms of PDR, throughput and end-to-end delay. Using the idea of tree packing,

M. Sanna and E. Izquierdo [4] presented a detailed routing algorithm for network coding based multicast. They analyzed the algebraic model of network coding. The authors

Wireless Network Coding Applications	Applications Type	References
Routing Protocol (Sec 4.1)	Routing problem in network coding. Routing algorithm for network coding based multicast. Cooperative network coding. Distributed rate control algorithm for multicast session in ad hoc networks. Joint optimization problem for routing, channel assignment, and network coding.	[3],[5],[16],[17],[18],[19],[20],[21],[22],[23],[24].
Throughput Modeling and Analysis (Sec 4.2)	Network throughput gains model for wireless conventional network coding and analog network coding. Joint link scheduling, channel assignment and routing algorithm to obtain optimal network throughput. Improve the throughput in wireless networks for multiple unicast sessions. Analyze end-to-end throughput in a multihop wireless network with network coding. joint power control and routing with random linear network coding to improve throughput for the single source multicast	[20],[25],[26],[27],[28],[29],[30][31],[32],[33],[34][35],[36],[37],[38],[39],[40],[41],[42],[43],[44],[45],[46].
Delay Modeling and Analysis (Sec. 4.3)	Analytical approach for end-to-end delay performance analysis of each flow in wireless networks. Theoretical formulations for computing the delay bounds of burst flows in wireless network coding. Addressed the problem of minimum average packet delay of Multi-hop Wireless Networks (MWN), which uses network coding. Improve packet transfer delay and jitter of receiving packets. Throughput-delay tradeoff in large-scale mobile wireless ad hoc networks employing Reed-Solomon (RS) coding.	[47],[48],[49],[50],[51],[52],[53],[54],[55],[56],[57],[58].
MAC Protocol (Sec. 4.4)	Cross-layer design possibilities of joint medium access control (MAC) and network coding. Joint design of network coding and MAC in wireless ad hoc networks. Study the effects of MAC protocol on the performance of wireless network coding. Cross-layer optimization in MAC and network layers for wireless multicasting with multiple cooperative source nodes.	[59],[60],[61],[62],[63],[64],[65],[66],[67],[68],[69],[70].
Cross layer Design and Optimization (Sec. 4.5)	Cross-layer algorithm for joint optimization of congestion control, routing, and scheduling in multi-hop wireless networks with network coding. Partial network coding with decode-and-forward cooperative diversity scheme that mitigates error propagation due to channel imperfections in wireless ad hoc networks. Cross-layer optimization framework to derive the maximum throughput region through the joint selection of MAC and network layer strategies for saturated multicast traffic.	[71],[72],[73],[74],[75],[76],[77],[78],[79],[80],[81],[82].

Wireless Network Coding Applications	Applications Type	References
	Design coding and scheduling algorithms for optimizing the performance of network coding jointly with the MAC and PHY layers. Cross layer method for interference cancellation and network coding, that significantly increases the capacity of multi-hop wireless networks.	

concluded the goal of the routing problem in network coding is to build edge-disjoint paths from the source to each receiver.

In [5], a detailed routing algorithm for network coding based multicast is presented. T. Shaoguo et al. [5] proposed a detailed method to find proper transmission paths from source to multi-receivers in a multicast network while using random network coding. In addition, Z. Jin and Z. Qian [17], proposed the idea of cooperative network coding (CNC) to exploit spatial diversity for improving coding opportunity, and provide a theoretical formula for calculating the maximal throughput of unicast traffic that can be achieved with CNC in multi-rate wireless networks. They discussed how to exploit cooperative network coding for route selection in multi-rate wireless networks. A. Argyriou and A. Pandharipande [18] presented a cooperative protocol that exploits analog network coding (ANC). The authors considered a system with cooperative relaying of overlapped transmissions from two independent users. They explored the case that the network nodes may allow the transmitted signals to interfere both at the final destination node and at an intermediate node that acts subsequently as a relay. X.-N. Miao et al. [19] have developed a distributed rate control algorithm for multicast session in ad hoc networks. The algorithm with random network coding can be implemented in a distributed manner and work at the transport layer to adjust source rates and at the network layer to carry out network coding. The scheduling element of our algorithm is a dynamic scheduling policy.

In [20], a model of the network throughput gains of two types of wireless network coding (WNC) schemes, including the conventional NC and the analog NC schemes, over the traditional non-NC transmission scheduling schemes in multi-hop, multi-channel, and multi-radio wireless ad hoc networks are proposed. The authors proposed an analytical framework for deriving the network throughput gain of the wireless NC schemes over general wireless network topologies. They proposed a joint link scheduling, channel assignment and routing algorithm approach obtain an optimal network throughput.

G. Fengyuan et al. [21] studied the multicast capacity gain with network coding in static ad hoc wireless network. The authors focused on the capacity gain with network coding in static multicast tree transmission instead of unicast network under the system model of Li's [22]. Z. Xinyu and L. Baochun [16] showed how the network coding able to further increases the capacity of multi-channel wireless mesh networks. The authors proposed a joint optimization problem that accounts for routing, channel assignment, and network coding schemes. In addition, they designed a decentralized algorithm that naturally combines network coding with traditional routing, under arbitrary channel assignment schemes. In [23] the authors applied the idea of cooperative networking with network coding and design a novel anonymity based wireless mesh networks. The design is built upon the classic Onion Routing protocol, to achieve a higher throughput, while still preserving user privacy in wireless mesh networks.

In work [24] the authors considered a network that supports multiple multicast flows with network coding. They consider the intra-flow network coding and linear network coding only, which can be shown to maximize the capacity region for single-source multicast traffic. The authors proposed a packet scheduling algorithm so that synchronization buffers can be bounded by a finite constant that only depends on the maximum hop count of the flows.

4.2 Throughput Modeling and Analysis with Network Coding

Network coding (NC) has been regarded as a promising technology for throughput improvement in wireless networks. H. Su and X. Zhang [20] presented a model of the network throughput gains of two types of wireless network coding (NC) schemes, including the conventional NC and the analog NC schemes. The authors proposed an analytical framework for deriving the network throughput gain of the wireless NC schemes over general wireless network topologies and proposed a joint link scheduling, channel assignment and routing algorithm approach to obtain optimal network throughput.

In [25], the authors have studied the network throughput gains of two types of wireless NC schemes, the conventional wireless NC and the analog NC respectively over the traditional non-NC scheme in multi-hop, multi-channel, and multi-radio wireless networks. They formulated a general linear programming framework for solving the throughput optimization problems for the traditional non-NC scheme and for the two types of wireless NC schemes. The framework is applicable to any transmission schemes with or without NC to maximize the network throughput for any wireless network topologies. Umehara et al., [26] have analyzed and provided expressions for the throughput and packet delay on two hop wireless relay networks with and without network coding from a theoretical perspective of the slotted ALOHA protocol. The authors have shown the trade-off between the capacity and its delay, according to the transmission probability of the relay node. Therefore, the transmission probability of the relay node should be selected properly according to the system requirements and node traffic.

D. Umehara et al., [27] have proposed a general analytical model for single-relay two-hop wireless CSMA systems both with and without network coding as an extension of two-hop wireless slotted ALOHA systems. The proposed analytical model provides a criterion for the transmit probability at the relay node to maximize the throughput for any given transmit rate of end nodes. Furthermore, it is clarified that the throughput for two-hop wireless CSMA systems can be enhanced as compared to that for slotted ALOHA systems in case of non-hidden end nodes whereas it deteriorates considerably in the case of hidden end nodes. In addition, the authors clarified that the throughput can be enhanced by employing the CSMA protocol in case that the end nodes are not hidden each other. On the other hands, they have clarified that the throughput for CSMA systems is less than that for slotted ALOHA systems in case of hidden end nodes.

A new analytical model for stable throughput evaluation of wireless network coding based on specific random access MAC and network coding schemes is presented in [28]. The proposed model includes two basic processes of network coding, i.e., packets combination and packets multicasting. The authors considered and focused on the arrival and departure rates in and from the wireless nodes respectively, rather than the nature of arrival and departure processes in steady state. In [29], the authors analyzed the end-to-end throughput performance model for IEEE 802.11 wireless network with network coding. They considered an IEEE DEC protocol and linear topology in which traffic sources are located at both ends and intermediate nodes act as relays with a coding rule. The model is an extension of quantitative analysis to analyze the network coding mechanism. The numerical results demonstrated that the analytical model is sufficiently accurate and can be utilized in the design of IEEE 802.11 wireless networks with network coding.

J. N. Liu et al., [30] established bounds on the throughput benefit of network coding and broadcasting for multiple source multicasts in random networks. The authors showed that network coding and broadcasting lead to at most a constant factor improvement in per node throughput. A physical-layer network coding (PLNC) effectiveness of the throughput improvement for multi-hop multicast in random wireless ad hoc networks (WAHN) is studied [31]. Y. E. Sagduyu et al., [32] addressed the problem of exchanging broadcast packets among multiple wireless terminals through a single relay node. The objective is to evaluate the delay and throughput gains of network coding over plain routing. The authors compared plain routing, digital network coding at the packet level with analog network coding based on scheduled or random access of terminal transmissions that are forwarded by the relay node for multiple terminals exchanging packets through a single relay. The results showed that analog network coding (based on schedule or random access) improves the delay and throughput over a digital network coding for error-free channels. Fundamental limitations to the benefit of network coding in terms of energy and throughput in multihop wireless networks is established [33].

In terms of throughput and energy saving, the authors proved that the gain of network coding of a single multicast session is at most a constant factor. The authors [33] adopted two well accepted scenarios in the field single multicast session and multiple unicast sessions. In addition, the authors present a lower bound on the expected number of transmissions of multiple unicast sessions under an arbitrary network coding. The authors [33] found the gain of network coding on the throughput of large scale homogeneous wireless networks is asymptotically bounded by a constant. The results showed that network coding can improve the throughput in wireless networks by at most a constant factor, which is determined by the parameters of the underlying wireless channel model. In addition, the authors computed a novel lower bound on the expected number of transmissions. They studied the benefit of network coding in terms of the throughput of wireless networks for multiple unicast sessions. The authors [33] focused on two popular network scenarios: single multicast session and multiple unicast sessions.

D. Zeng et al. [34] studied the throughput of two-hop wireless network coding and investigated how the maximum throughput can be achieved under a random medium access scheme. The authors considered a more practical network where the structure of overhearing status between the intended receivers and the transmitters is arbitrary. Upon the concept of network coding cliques (NCCs), the authors [34] made a formal analysis on the network throughput using network coding. Also, the authors [34] found that the maximum throughput can be achieved under a random medium access scheme when the medium access priority of the relay node is equal to the number of NCCs in the network. Joint scheduling and network coding in wireless multicast networks with independent sources is studied [35].

The authors [35] formulated a linear optimization problem whose results can be used to design a coding solution. They presented statistics that showed the importance of incorporating unequal timeshares in designing network codes. The requirements of code construction algorithms for wireless networks that capture the broadcast property of these networks are presented [35]. The authors provided a framework that covers three consecutive steps: 1) scheduling, 2) optimization, 3) coding and derives sufficient information in each step. They have examined the problem of joint scheduling and network coding in wireless networks. A statistic to demonstrate the importance of incorporating unequal timeshares in designing network codes is presented. The authors showed that unequal time shares can improve the multicast throughput by 35% of maximum flow problems and will result in energy savings between 13% and 30% in minimum energy problems [35].

A trade-off between the throughput and coding overhead focusing on an intermediate node of a three-node chain topology and the relay node have two buffers, managing two packet flows separately have been considered in [36]. The per-flow throughput is analyzed with a continuous-time Markov chain, and the analysis is validated by simulation. The authors [36] analyzed the end-to-end throughput in a multihop wireless network with network coding.

N. H. Chau et al., [37]have proposed an approach namely Cross-Layer Network Coding (CLNC) that joints power control and routing with random linear network coding to improve throughput for the single source multicast problem in multicast wireless mesh networks. The authors [37] solved multicast problem using two algorithms. An optimal power algorithm is used to choose the best power level of node and network coding algorithms is used to transmit packets on the network. The authors [37] considered the first three layers of protocol stacks (physical, MAC and network layers) for cross-layer design. The simulation results showed that when the number of receivers is high, CLNC throughput is higher at least 30% than that of known methods such as AODV, DSDV and DSR and higher than that of MAODV.

P. S. David and A. Kumar [38] investigated the throughput and decoding-delay performance of random linear network coding in a wireless broadcast setting as a function of the coding window size and the network size in an unreliable single-hop broadcast network setting. Due to the poor performance of TCP over multi-hop wireless networks, the authors [38] have investigated what extent network coding can help to improve the throughput performance of TCP controlled bulk transferred over a chain topology multi-hop wireless network. The results showed that without any modification to the MAC protocol, the gain from network coding is negligible when the nodes use IEEE 802.11's DCF in CSMA/CA mechanism to perform distributed packet scheduling. The authors [38] provided a theoretical analysis that yields a throughput bound with network coding and proposed a distributed modification of the IEEE 802.11 DCF, based on tuning the back-off mechanism using a feedback approach. The inherent coordination problem of carrier sensing based random access in multi-hop wireless networks dominates the performance.

S. Karande et al., [39] used the protocol and physical models to show that the order throughput gain derived from NC for multicasting and broadcasting in wireless networks is bounded by a constant. As the network size increases, NC renders the same order throughput as traditional store-and-forward routing. K. Ronasi et al., [40] used a wireless network model with several unicast data sessions, multiple routing paths for each session, and adaptive channel coding at the physical layer to improve the successful throughput. The authors [40] showed that combination of multipath routing and adaptive channel coding can improve throughput and reduce delay and it is possible to trade off delay for throughput and vice versa. This is in contrast to the general expectation that higher throughput can only be achieved with noticeable degradations in the end-to-end network delay.

The authors in [41] and [42] indicated that the multipath routing improves the network performance by not only distributing the traffic over different links, but by providing alternative paths for those sessions that are exposed to high bit error rates due to environmental conditions as well.

N. Pappas et al., [43] investigated the performance that can be achieved by exploiting path diversity through multipath forwarding for end-to-end retransmissions. Network coding decreases the delay that is needed for the transmission of a packet compared to multipath and traditional single path forwarding, achieving a delay-throughput balance that lies between the corresponding performance of simple multipath and multi copy forwarding, which sends the same packet across all available paths. The gain from network coding increases as the number of available paths increases. A tradeoff between delay and throughput and comparison of network coding with other transmission schemes such as single path, multipath, and multi-copy are studied [43]. Also, the average delay per packet and the throughput achieved is analyzed during the queuing delay at the sender, the encoding and decoding delays, and the ACK transmission delays are ignored.

In [44] joint network coding and scheduling in wireless multicast networks with independent sources was proposed. The authors formulated a linear optimization problem whose results can be used to design a coding solution. The authors presented statistics that show the importance of incorporating unequal time shares in designing network codes. The statistics show a throughput improvement of about 35% in maximum flow problems and energy savings between 13% and 30%, depending on the network size,

Y. E. Sagduyu et al. [45] derived the maximum throughput region for relay assisted wireless broadcast with digital and analog network coding. The authors evaluated throughput and stability properties of wireless network coding for an arbitrary number of terminals exchanging broadcast traffic with the aid of a relay. The authors derived scheme of the coding and scheduling that used to minimize the number of transmissions needed for each node to broadcast one packet. The authors considered both DNC and ANC at the relay nodes. K. Chi et al. [46] proposed a general theoretical framework with a cross-layer consideration of physical layer, MAC layer and coding sub-layer to obtain the close-form expressions of throughput under both the non-network-coding scheme and the network-coding scheme. The authors clarified that the throughput greatly depends on the transmission priority of the relay node and further analyzed the optimal bandwidth allocation of relay node to maximize the throughput.

4.3 Delay Modeling and Analysis with Network Coding.

H. Li et al., [47] presented an analytical approach for end-to-end delay performance analysis of each flow in wireless networks that employ inter-session coding. The previous works on performance analysis in wireless network coding mainly focused on the throughput of the overall network. Network calculus is used as the theoretical basis of the approach. There are three specific problems: identifying traffic flows, characterizing broadcast links, and measuring coding opportunities, that must be taken into consideration by applying network calculus to the analysis of wireless network coding. The authors [47] introduced three main contributions. First, theoretical formulations for computing the delay bounds of burst flows in wireless networks employing network coding is obtained. Second, the factors affect the end-to-end delays, and find an interesting phenomenon that, as traffic grows, the overall delay can potentially decrease. Third, a new scheduling scheme that can improve the performance of current practical wireless network coding is introduced.

H. Li et al. [47] classified three main problems in wireless network coding. First, in order to identify the traffic flows in the network, the concept of information flows is used. Second, a dummy output model for each node is presented. Third, a metric of coding opportunities is definite to compute the service curves that a node provides for the information flows. M. Alvandi et al., [48] addressed the problem of minimum average packet delay of Multi-hop Wireless Networks (MWN), which uses network coding. The authors have studied the capacity allocation in MWNs that employs network coding. In order to exploit the broadcast nature of the wireless medium, which is a natural setting for network coding, they assigned capacities to different nodes. In addition, an NLP is formulated to minimize the average packet delay of MWNs.

Y.-S. Kim et al., [49], have shown the network coding delay for a multi-hop path between source and destination along which multiple coding points are permitted to reside. The authors [49] analyzed the delay since the source sends the first packet of a generation until the destination acquires the original packets from the coded packets through numerical analysis and simulation. A new concept of r-hyper arc for the numerical analysis is introduced to consider the overhearing which is the unique feature of the wireless network. The authors [49] showed that the network coding can improve the delay noticeable and the gain increases, as more coding points exist in the network. However, the increase is limited due to the limited number of available disjoint paths from the source to the destination.

Y. Xiaoji [50] focused on the analysis of the average block delay modeling in lossy wireless multicast networks. Combining the 802.11 delay model and network coding multicast behavior in wireless networks with the packet delay constraint and aims at minimizing the number of packets is presented in [51]. The authors [51] proposed a graph model to describe the relationship between packets and proposed an encoding algorithm based on the maximum weight clique in the graph to help the sender decides how to broadcast.

Quantitative analysis for the performance of the wireless broadcast algorithm based on network coding from the delay perspective is presented in [52]. Queue theory is used to calculate the delay of M/G/1 model, with the input could be seen as Poisson stream and the output as a general process. In [53], a novel NC-based retransmission method considering packet reordering delay in order to improve packet transfer delay and jitter of received packets is proposed. To realize this, a scheme to hand up packets is established.

The authors [53] proposed a new algorithm to select the member packets encoded together, aiming to decrease the reordering delay. The literature specifically has focused on applying NC to retransmissions of lost packets in IEEE 802.11 Distributed Coordination Function (DCF), which is the primary channel access method in wireless LAN, adopts Automatic Repeat reQuest (ARQ) to retransmit lost packets. The authors [53] showed through the simulation that the proposed method can improve packet transfer delay and jitter, while keeping the same packet reception rate compared to the sort by time method.

In order to improve the packet transfer delay and jitter of receiving packets, a novel NC-based retransmission method is proposed [54]. Additionally, to achieve more improvement of delay, jitter and retransmission efficiency, the authors [54] proposed a retransmission method in which the NC-based retransmission cooperates with the typical ARQ method.

Z. Kong et al., [55] studied the throughput-delay tradeoff in large-scale mobile wireless ad hoc networks employing Reed-Solomon (RS) coding. The authors [55] proposed a 2-hop relay with Reed-Solomon coding (2HRRSC) scheme and showed that while maintaining a constant Θ (1) throughput, 2HRRSC scheme can achieve a delay scaling of Θ (n) under the random walk mobility model studied. The results in literature [55] have shown that the per source-destination pair throughput can be improved from Θ $(1/\sqrt{n \log n})$ to Θ (1), if nodes are allowed to move and a 2-hop relay scheme is employed.

An optimization of the delay performance in reliable multicast data stream to a set of one-hop receivers from the receiver perspective is presented [56]. W.-L. Yeow et al., [56] analyzed the system based on queuing theory using semi-Markov chains from both the system-wide and receiver perspectives. The authors found that the average delay per received packet at the receivers' end can be minimized by appropriate scheduling of data packets and appropriate size of the coding buffer, which depends on the rate of the incoming data stream and capacities of the receivers. The authors [56] presented an analysis of the delay performance of two multicast streaming methods at per-receiver and system-wide perspectives. The first method is a pure random linear coding and the second is a hybrid network coding which can reduce delay. Moreover, an adaptive multicast method that minimizes the average delay per received packet, while improving capacity through network coding is proposed [56]. H. Zeng and W. Chen [57] presented the optimal delay energy trade-off curve in continuous time domain. The authors observed that first-come-first-serve policy is not sufficient to achieve the minimized delay. The authors proposed an Enhanced Network Coding (ENC), an extension to ONC [58] in continuous time domain. In ENC, the relay transmits both coded and uncoded packets to reduce delay. The authors presented the packet delay, packet-loss rate, and average energy consumption of ENC using a Markov model for general renewal process queuing and classical Poisson process queuing.

4.4 MAC Protocol with Network Coding

In wireless networks, network coding has been considered as an effective approach that utilizes the broadcast nature of the wireless channel to achieve energy efficiency and improve the network throughput [10], [16], [25], [34], [36]. While network coding can be utilized in different forms of communications, including unicast, multicast and broadcast, the MAC layer transmissions used for network coding are mainly multicast, therefore, such network coding based communications are substantially affected by the performance of the underlying MAC layer multicast.

Y. E. Sagduyu and A. Ephremides [59] studied the cross-layer design possibilities of joint medium access control (MAC) and network coding. In addition, a time-dependent flow optimization problem for joint MAC and network coding is formulated and a basic method to construct a time-varying linear network codes is assumed. In addition, the authors [59] introduced practical solutions that depend on graph colouring to derive network codes and conflict-free transmission schedules on simplified sub tree network representations.

A cross-layer optimization framework is formulated to derive the maximum throughput region for saturated multicast traffic in [60]. The authors [60] showed that the contents of network flows are specified through network coding in the network layer and the throughput rates are jointly optimized in medium access control layer over a fixed set of conflict-free transmission schedules. Also, they showed that the network coding improves throughput rates over plain routing and achieves the largest gains for broadcast communication and intermediate network sizes. Throughput optimization imposes fundamental tradeoffs with the transmission and processing energy costs such that the throughput-optimal operation is not necessarily energy efficient.

X. Deng and Y. Yang [61] proposed a novel MAC layer multicast protocol based on IEEE 802.11 that can be used in network coding algorithms to achieve reliable and efficient communications called as NC-MAC. The performance of NC-MAC for two typical network coding algorithms through NS-2 simulations is evaluated. The results demonstrated that the superior performance of NC-MAC is over other MAC protocols in maintaining both reliability and efficiency. The use of control frames, including RTS, CTS and ACK in NC-MAC, provides sufficient MAC layer delivery guarantee, while the unique local retransmission policy and the receiver list update maximize the benefit of random network coding. Y. E. Sagduyu and A. Ephremides [62] considered the joint design of network coding and medium access control (MAC) in wireless ad hoc networks. The authors considered a slotted wireless network with links modeled as classical collision channels. A practical solution that relies on graph coloring to derive the network codes on the simplified sub tree graphs and converts them to the conflict-free transmission schedules is presented.

H. Li et al., [63] studied the effects of MAC protocol on the performance of wireless network coding. The authors introduced the dummy topology graph (DTG) of a wireless network that can properly describe the broadcast property of wireless channels to model the MAC protocols. They have derived theoretical formulations for computing the end-to-end delay of the flows using the theory of network calculus. The authors have showed through the results on the effects of MAC protocols on the per-flow performance of wireless network coding especially on the end-to-end delay of each flow in the network. The fairness of MAC protocol can help to improve the performance of the network. Y. E. Sagduyu and A. Ephremides [64] addressed with the problem of cross-layer optimization in MAC and network layers for wireless multicasting with multiple cooperative or competitive source nodes in a simple tandem network. The authors [64] considered scheduled or random access in MAC layer and model network layer operation as network coding or plain routing.

R. Niati et al. [65] investigated the problem of network coding and media scheduling in wireless multihop networks. The authors suggested a new code design constraints for wireless networks depending on the unique characteristics of the wireless media, such as omni-directional transmissions and destructive interference, as well as the limitations of wireless nodes to either transmit or receive at any given time. The authors investigated necessary and sufficient conditions to design a capacity-achieving network coding solution for wireless networks. The proposed approach works only if all of the code characteristics of the wired graph in the wireless one are reserved.

L. Scalia et al., [66] proposed a network coding based scheme specifically designed to enhance TCP performance over IEEE 802.11 multi-hop wireless networks, called Piggy Code. The root of this approach is a network-coding module operating between the Network and the MAC layer. Each node running Piggy Code encodes, whenever it is possible, TCP-DATA and TCP-ACK packets belonging to the same information flow. The coding approach is theoretically analogous to piggyback the CPACK packet within the TCP-DATA packet, with the substantial difference that, by performing network-coding operations, the actual packet size remains unchanged. Piggy Code operates at a different layer and independent from the TCP version used. It can deploy with the standard TCP as well as enhance the TCP versions because it does not directly modify the TCP policies. Piggy Code cooperates with the routing in order to maximize the network coding opportunities.

R. Niati et al. [67] studied joint scheduling and network coding in wireless multicast networks with independent sources. The authors formulated a linear optimization problem whose results can be used to design a coding solution. Designing a network coding and scheduling solution for wireless networks involves three consecutive steps: scheduling, optimization, and coding. A framework that covers all three steps and derives sufficient information in each step to serve as input of the following step is provided. In [68] the authors have studied a scheme to integrate an existing wireless network coding architecture with cooperative diversity protocol where idle terminals may be transformed into relays. The authors used the COPE architecture [14] to test the ideas and attempted to work in both physical and MAC layers. The authors have shown that having terminals cooperating as relays would improve the performance of transmission over each link, consequently increasing the overall network performance.

In [69] the authors proposed a modification at the MAC and PHY layers of the 802.11 protocol using a Software Radio (SORA) platform to support WNC. The results show that network coding (at the MAC or PHY layer) increases system throughput-typically by 20–30%. S. Tarapiah et al. [70] proposed a network coding scheme in wireless ad hoc networks in both realistic MAC and physical layers are considered and when mobility of nodes is considered as well. The performance analysis of the proposed network coding scheme on broadcasting traffic is strongly depends on the network node density and the generation size.

4.5 Cross layer Design and Optimization with Network Coding.

L. You et al. [71] presented a cross-layer algorithm for joint optimization of congestion control, routing, and scheduling in wireless multi-hop networks with network coding. The authors introduced virtual flow variables in the formulation of the capacity region of the networks. K. Li and X. Wang [72] have developed across-layer optimization framework optimal design for multi-radio multi-channel wireless mesh networks with employing network coding to support multiple unicast applications. The authors [72] proposed a network code construction scheme based on linear programming and a column-generation-assisted primal dual method to solve the optimization problem. P. Poocharoen et al., [73] have proposed a partial network coding with decode-and-forward cooperative diversity scheme that mitigates error propagation due to channel imperfections in wireless ad hoc networks. The proposed combines opportunistic network coding, opportunistic listening, and opportunistic cooperation together. Also, they designed a cross layer scheme between MAC and physical layers.

A. Argyriou [74] presented a cross-layer framework for optimizing the performance of opportunistic network coding in wireless multihop networks. The target scenario considers a wireless ad hoc network (WANET) with back logged nodes and with multiple unicast packet flows. The author focused on modeling the expected network-coded throughput individually for each wireless station as a function of parameters at the lower layers, like the maximum number of link-layer retransmissions and the transmission mode at the physical layer (PHY). The author focused entirely on optimizing the performance of network coding jointly with the medium access control (MAC) and PHY layers to model analytically the impact of coding decisions on the system throughput and then used this model for the design of coding and scheduling algorithms.

Y. E. Sagduyu and A. Ephremides [75] formulated a cross-layer optimization framework to derive the maximum throughput region through the joint selection of MAC and network layer strategies for saturated multicast traffic. A dynamic queue management strategy is used to expand the stability region towards the maximum throughput region. The authors [75] investigated the throughput improvement strongly benefits from the cross-layer design across MAC and network layers. A. Khreishah et al., [76] presented a new flow based characterization of pair wise intersession network coding (coding across two unicast sessions). An optimum joint coding, scheduling, and rate-control scheme can be devised and implemented using only the binary XOR operation. The new scheduling/rate-control scheme proves provably the throughput degradation with imperfect scheduling, which facilitates the design tradeoff between the throughput optimality and computational complexity of different scheduling schemes.

W. Chen et al. [77] presented a novel cross layer method for interference cancellation and network coding, which significantly increases the capacity of multi-hop wireless networks. The authors [77] decomposed the multi-hop network into a cell-like sub-network, they presented a cross layer method for interference cancellation and network coding. In cell-like sub networks, the nodes communicate with each other via a relay and each packet is delivered over two hops. There are two cross-layer strategies that are considered, namely cross layer interference cancellation and joint physical-network coding. By comparing these two conventional single-layer schemes, namely successive decoding (dirty-paper coding) and absolute network coding, the proposed approach can significantly increase the capacity region and reduce the power consumption in the relay node. It was also demonstrated that in a two-node wireless switching network, joint physical-network coding can achieve a 200% sum-capacity gain over the successive decoding, for instance.

M. S. Moghaddam et al. [78] proposed a cross-layer transmission based on rate less coding for relay networks. In the proposed method, rate less coding is used at the packet level and a separate physical layer coding is used in the physical layer. As rate less codes are originally designed and optimized for erasure channels, using these codes at the physical layer can lead to significant performance degradation. The proposed scheme has the advantage of a cross-layer design, which uses a rate less code at the packet level modeled by an erasure channel. The paper [78] presented two rate less transmission schemes namely the physical layer rate less transmission and cross-layer rate less transmission.

Two rate less transmission schemes have been discussed and their performances have been analyzed. One scheme is based on rate less coding at the physical layer while the other uses rate less coding at the packet level and encodes each packet by a physical layer rate-R code. The authors showed through the simulation results that the performance of the cross-layer rate less scheme is better than the performance of physical layer rate less scheme in terms of the average time required for successful decoding a specific number of packets. It should also be noted that although in this paper, relay nodes use the same rate less code, in general, different rate less codes can be used by different relays, while an information combining receiver is used at the destination.

Y. Cao and S.D. Blostein [79] proposed a cross-layer scheme to optimize physical layer modulation and coding rate to maximize system throughput. In this work, both slow and fast fading channels are considered. For slow fading channels, cross-layer adaptive modulation and coding schemes are also proposed. Numerical results showed that the proposed cross-layer schemes outperform traditional schemes significantly in terms of system throughput. The authors [79] investigated optimization of the QoS tradeoff between the physical-layer and the application-layer for rate less coded systems in fading channels. The application layer rate less code is assumed to keep generating the coded packets on the fly until all erroneous packets are corrected.

K. Chi et al., [80] studied the application of rate-adaptive transmission mechanism in network coding based multihop wireless networks. In such networks, whether a coding solution is satisfactory depends not only on the number of involved native packets, but also on the packet loss probabilities of the intended next hops and the transmission time, both of which depend on the transmission rate. An efficient algorithm for jointly finding better combinations of coding solution and transmission rate is proposed. In the coding-based transmission scheme, two new features make the rate selection much different from that in the non-coding transmission. A metric for measuring the efficiency of transmitting one encoded packet at a specific rate is defined. The joint design of coding operation and rate selection to maximize the node transmission efficiency in network coding-based multihop wireless networks are studied. A new problem that arises when a base station in a broadband wireless network wishes to multicast information to a large group of nodes is defined and addressed [81].

On the other hands, to guarantee some level of reliability using application-layer forward error correction (FEC) codes. The new problem is to determine which PHY-layer modulation and coding scheme (MCS) the base station should be used for each packet. The authors [81] presented several variants of this problem, which differ in the number of automatic repeat request (ARQ) rounds during which the delivery of a data block must be completed. Most of these variants are shown to be NP-hard. An optimal solution for practical instances is presented where the number of MCSs is small and efficient approximations and heuristics for the general case of each variant. The results demonstrated that the base station can improve the performance of multicast by optimizing the selection of a modulation and coding scheme (MCS) for each individual packet.

J. Hwang and S.-L. Kim [82], have considered the CSMA/CA multihop networks where the two end-nodes transmit their packets to each other and each intermediate node adopts network coding for delivering bidirectional flows. The authors [82] focused on a wireless multihop network in which bidirectional traffic flows and network coding are adopted on each relay node. The spatial reuse of a radio channel in this network is mostly related to the MAC scheme, e.g., carrier-sensing multiple access/collision avoidance (CSMA/CA) mainly because the carrier-sensing (CS) mechanism prohibits neighboring nodes from reusing the channel. It has been noted that the physical CS scheme brings out some problems: hidden-node problem and exposed-node problem. The former problem can be solved with virtual CS, which uses request-to-send (RTS) and clear-to-send (CTS) control packets and network allocation vector (NAV), while the exposed-node problem still remains and controversy surrounds it.

5. Summary

In this survey paper, we presented an overview of the recent researches on wireless network coding. Firstly, we mentioned the advantages and disadvantages of network coding. The types of wireless network coding is presented. Furthermore, we divided the wireless network coding related work into five research areas, which includes routing protocols, throughput modeling and analysis, delay modeling and analysis, MAC protocols, and cross layer design with optimization. Wireless network coding is considered as a new transmission paradigm that proved the strength in optimizing of network resources. Network coding is considered as a generalization of conventional store-and-forward routing techniques. Researchers have proven that network coding has great potential to improve network throughput and packet delivery ratio, reduce delay, and improve robustness in multi-hop wireless networks by exploiting the intrinsic broadcast nature of wireless communication.

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نظرة عامة عن تشفير الشبكات اللاسلكية

الملخص: تطورت شبكة التشفير (Network coding) في السنوات الأخيرة عبر الشبكات اللاسلكية، لذلك هناك المزيد من الاهتمام في هذا المجال من مجتمع الباحثين. شبكة التشفير هي تقنية قادرة على تعزيز موثوقية وكفاءة أنظمة اتصالات الشبكة. تمتلك تقنية شبكة التشفير القدرة على تمكين العقد الوسيطة من دمج الحزم المستلمة مسبقا وإرسالها. شبكة التشفير لديها ميزتين رئيسيتين: تحسينات في الصلابة والإنتاجية. وفي هذه الورقة، يتم تقديم مسح وعرض الأعمال والبحوث السابقة لتشفير الشبكة في بيئة لاسلكية. لقد بدأنا بمناقشة الخصائص الأساسية، فوائد و مساوئ تشفير الشبكة. ثم قمنا بتلخيص أنواع شبكة التشفير وقدمنا مراجعة أدبية لتطبيقات تشفير الشبكة مع بروتوكول التوجيه ونمذجة العطاء والتأخير ، وبروتوكول MAC وتصميم الطبقات المتقاطعة.

الكلمات المفتاحية: تشفير الشبكة، تشفير الشبكة اللاسلكية، نمذجة العطاء/ التأخير، بروتوكولات التوجيه/ التحكم بالوصول إلى الوسائط، تصميم الطبقات المتقاطعة.