

Network Coding Based Link Scheduling for QoS Provisioning in Multi-radio and Multi-channel Wireless Mesh Networks

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Abstract—This paper addresses Quality-of-Service (QoS) improvement in wireless mesh networks (WMNs) with multi-radio multi-channel by applying a novel network coding technique. It is known that network coding over wired networks enables connections at rates that cannot be achieved by traditional routings. However, the properties of wireless networks (e.g., omnidirectional transmissions, destructive interference, single transceiver per node, finite energy) modify the formulation of network coding and deviate from the classical network coding approach used in wired networks. In this paper, we investigate the problem of network-wide data transmission under the consideration of QoS requirements (namely packet delivery ratio, packet delay) over multi-radio and multi-channel WMNs. To solve this problem, we first introduce a network coding method, namely COPE, which is used to increase network-wide throughput for unicast wireless networks, and then present an Integer Linear Programming formulation of a given multi-radio and multi-channel WMN for addressing network coding traffic, routing, QoS requirements and scheduling optimizations. The proposed analytical formulation increases the network-wide throughput while satisfying the generalized QoS requirements by combining network coding strategy and interference free schedules. Our evaluations both in 16-node graph topology and 32-node random topology network show that a route selection strategy that is aware of network coding leads to higher in end-to-end throughput when compared to coding-oblivious routing strategies.

Index Terms—Multi-channel Multi-radio, Wireless Mesh Networks, Network Coding, QoS, Liner Programing, Scheduling Algorithm

I. INTRODUCTION

Wireless mesh networks (WMNs) are being used as the last mile for extending the Internet connectivity for mobile nodes. Traditional wireless systems used in the industry in recent years are mostly cellular radio links,

using point-to-point or point-to-multipoint transmission. These systems have limitations and liabilities. For example, such a network usually has a rigid structure, requires a careful planning, and the wireless channel usually drops signals and degrades performance. Compared with traditional wireless systems, WMNs are more suitable for real life applications needed today [1]. WMNs the emerging network technologies that employ wireless multi-hop networking to provide a cost-efficient way of accessing broadband Internet for community or enterprise users in rural areas, municipal and metropolitan networks. A typical WMN contains mesh routers (MRs) and mesh clients (MCs). MRs have limited mobility and connect wired Internet connections, while MCs access to the Internet through MRs and share network resources among themselves. For WMNs, the aggregate traffic load of each routing node changes infrequently. For the natural that communication channels are share by the wireless terminals, the signal sent by a wireless terminal will be received by all other terminals within its transmission range and may cause interference to some terminals that are not the intended receivers. Thus, one of the major problems facing wireless networks is the reduction of capacity due to interference caused by simultaneous transmissions. Using multiple radios and multiple channels can alleviated interference because the probability of neighboring transmitting nodes using the same channels decreases, due to the availability of more radios and more channels to be scheduled at a certain time slot.

Another challenge for the wide deployment of WMNs is to provide Quality of Service (QoS) support for different applications. These networks usually provide elastic services such as file transfer, email, and remote terminal. In addition, these networks also provide real-time services including video and voice applications with specific transmission rate requirements, and are very

sensitive to latency and jitter. QoS support for real-time applications over multi-radio and multi-channel WMNs is still an open problem [1]. This problem calls for a new framework that could characterize the traffic demand uncertainty and integrate its effect into optimal network routing.

To answer this call, there are a number of researchers investigating the problem of throughput, QoS requirements in the multi-channel and multi-radio WMNs [2]-[11]. However, only few studies take into account the QoS requirements of using network coding technology. In this paper, we take advantages of network coding and the characters of multiple channels and multiple radios in order to improve network throughput while satisfying the generalized QoS requirements.

Network coding is a mechanism available to improve capacity of wireless networks [12]-[15]. The essence of the technology lies in conveying more information in each transmission by processing information from multiple sources at intermediate nodes leading to increasing overall network throughput. The idea of network coding was first applied in the context of multicasting in traditional wired networks [2]. Recently, it has been found that WMNs offer great background for network coding, given that wireless transmissions are inherently broadcast at physical layer and thus with coding yields better throughput even for unicast applications [16].

A simple example of transmissions among three nodes using network coding is shown in Figure 1. Two nodes exchange information through a common router (or an intermediate node) [16]. In this paper, we investigate on the problem of providing QoS support, while increasing throughput over the network-wide by using network coding technology. The goal of this paper is to develop strategies integrating the benefits of network coding to pursue for network-wide throughput improvement and satisfaction of QoS requirements.

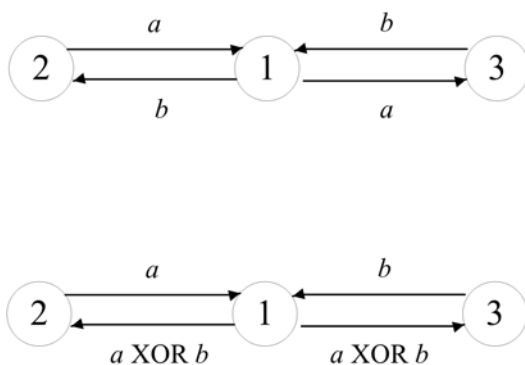


Figure 1. An example of information exchange with network coding

The rest of this paper is organized as follows. Section II discusses the related works. In Section III, we propose the system models and assumptions. In Section IV, we formulate the problem in WMNs and propose analytical routing model by using linear programming method for a given multi-radio and multi-channel WMN, addressing network coding traffic, routing, QoS requirements and

scheduling optimizations. Section V designs the directional link scheduling and channel assignment algorithm for wireless mesh networks. Section VI evaluates the proposed algorithm under a variety of general wireless mesh network topologies. In Section VII, The contribution of this paper is the linear programming formulations to the problem of optimizing throughput while satisfying the generalized QoS requirements and a centralized algorithm is further proposed. The proposed algorithm achieves approximately 11%~25% over the classic ones.

II. RELATED WORKS

In this section, we first introduce network coding technology used in this paper, and then review the existing routings considering QoS support for multi-channel and multi-radio WMNs.

The notion of network coding to enhance utilization was first proposed by Ahlswede *et al.* [12] in the context of multicast communication, Since then a large number of researchers have searched for efficient construction of network coding, e.g., Ref. [14]-[19]. On the matter of wireless networks, Lun *et al.* [20] studied the problem of minimum cost multicast involving a single session with one single source node. Ramanoorthy *et al.* [21] derived results for maximum flow achievable in random wireless networks for a similar single multicast session with a single source.

Recently, some works have focused on providing efficient unicast communications using network coding [22]-[26]. The COPE mechanism [22] considered WMNs with multiple unicast flows and it showed that network coding can increase the throughput of WMNs. COPE extended the gain of coding beyond the aforementioned information exchange scenario through opportunistic coding of two or more burst packets in a single transmission. COPE achieved this by having nodes overhear other transmissions in their neighborhoods and issue reception reports to let neighbors learn about the packets they currently had. However, COPE did not discuss upper layer strategies, such as routing decisions leading to the loss of coding opportunities and throughput. Li *et al.* [23] showed that in some multi-hop wireless scenarios with multiple unicast sessions, network coding would provide marginal benefits over traditional approaches without involving network coding. Ho *et al.* [24] considered network codes restricted to XOR coding between pairs of flows. In Ref. [25], the authors proposed centralized coding-aware routing schemes for maximizing the overall coding opportunities in the whole network by using programming, which was known to have the scalability issue and was difficult to employ in large, dynamic networks. The Medium Access Control (MAC)-independent Opportunistic Routing & Encoding (MORE) protocol [26] adopted a different strategy for supporting coding-aware, which randomly mixed packets before forwards them. This randomness ensured that router that heard the same transmission did not forward the same packets and consequently MORE needed no

special scheduler to coordinate routers and could run directly on top of 802.11.

Providing QoS support for flows in wireless networks is an active research area, and several classic researches can be found in Ref. [2]-[5]. SWAN [2] provided service guarantee for real-time flows by controlling the rate of elastic flows. The rate control algorithm used in SWAN was additive increase, multiplicative decrease (AIMD). One drawback of SWAN was that it lacked fair rate allocation for elastic flows. Expected Transmission Count (ETX) [3] and Weighted Cumulative ETT (WCETT) [4], based on shortest-path routing, extended short-path routing and took QoS requirements into consideration. ETX measured MAC transmissions and retransmissions to recover from frame losses depending on the link level packet errors caused by channel issues. WCETT was aware of the loss rate and the bandwidth of the link. WCETT did avoid intra-flow interference but did not guarantee the shortest paths or avoid inter-flow interference. iAWARE (interference aware) [5] considered intra-flow and inter-flow interference, medium instability, and data-retransmission time. By finding a path that was better in terms of reduced interflow and intra-flow interference for wireless networks.

Furthermore, a number of scheduling protocols are available for wireless networks. M.Alicherry [27] and M.Kodialam [28] studied the problem that how to satisfy a certain traffic demand vector from all wireless nodes by a joint routing, link scheduling, and channel assignment under certain wireless interference models.

To the best of our knowledge, there is no prior work analyzing the benefits of COPE-type opportunistic network coding for QoS provisioning in multi-channel and multi-radio WMNs to make routing decisions.

Our study is different from the aforementioned studies of routing strategies, which used network-coding technology to achieve a fraction of the maximum throughput or to balance the network-wide flow. In this paper, we propose a new coding-aware routing mechanism, which is applicable to wireless mesh networks with multiple unicast sessions. More specifically, our solutions are applicable to any multi-hop wireless network topology and any pattern of concurrent unicast traffic demands.

Our second contribution is that this paper introduces the notion of joint coding-aware and QoS-aware routing in multi-hop wireless networks.

Finally, this paper illustrates how a networking coding approach, such as COPE, can be integrated with a routing solution to further increase end-to-end throughput.

The difficulty of the optimization problem tackled in this paper arises from two aspects. First, for any given route, there are many possible combinations of coding opportunities at different nodes, so a subset needs to be selected from the available ones so as to optimize a global objective. Second, when the route is made aware of the coding opportunities, it has to choose between routing flows “close to each other” for utilizing coding

opportunities and “away from each other” to avoid interference.

Note that in this paper, we do not define a full-fledged network coding protocol, but instead focus on algorithmic analysis (using linear programming by Robert Vanderbei [29] that quantifies potential benefits across arbitrary wireless topologies, demands, as well as the impacts of the generalized QoS requirements. Our framework and its evaluation are fairly general, and they model the arbitrary interference between wireless nodes, the availability of different data rates, link loss rates, and other usual practical phenomenon observed in wireless environments.

III. SYSTEM MODELS

A. Network Models

We abstract the WMNs topology with nodes and the links corresponding to pairs of nodes within direct communication range as a graph $G=(V,E)$ [30]. $V=\{V_1, \dots, V_2\}$ is the set of terminals deployed in a plane, and E is the set of possible directed communication links. Let $E^-(i)$ denote the set of incoming links at node i , and $E^+(i)$ denote the outgoing links at node i . Furthermore, we let $e=(i,j) \in E$ represent a directed link $L_{i,j}$ in the network from node i and node j . Every terminal i has a transmission range $R_T(i)$ such that the necessary condition for a terminal j to receive correctly the signal from i is $\|i-j\| \leq R_T(i)$, where $\|i-j\|$ is the Euclidean distance between i and j . Notice that $\|i-j\| \leq R_T(i)$ is not the sufficient condition for $e=(i,j) \in E$. Some links do not belong to G because of either the physical barriers or the selection of the routing protocols. Besides, every terminal i also has an interference range $R_I(i)$ such that terminal j is interfered by the signal from i whenever $\|i-j\| \leq R_I(i)$ and j is not the intended receiver. Typically, $c_1 R_I(i) \leq c_2 R_T(i)$ for some constants $1 < c_1, c_2$. For simplicity, we define $R_I(i) = 2R_T(i)$ for all wireless nodes. We also use $L_{i,j}$ to denote the directed link (i,j) hereafter.

Assume that each terminal node i is equipped with $L(i) \geq 1$ radio interfaces, which is denoted as $k(i,1), k(i,2), \dots, k(i,L(i))$, and let $F=\{f_1, f_2, \dots, f_m\}$ be the set of m (orthogonal) channels that can be used by all wireless nodes. Moreover, we let $F(i,n)$ be the set of channels that can be used by the n th wireless interface $k(i,n)$ at node i , where $1 \leq n \leq L(n)$. In the literature, a wireless interface card can operate on all channels F . However in this paper, we assume a more practical case that each wireless interface can only operate on a subset of channels from F due to the hardware constraints.

Let $\delta(i,n,f_m) \in [0,1]$ be the indicator function of whether the n th wireless interface of node i can use f_m or not. Consequently, the channels can be used by a wireless node i is represented by a subset $F(i) \subset F$, where $F(i) = \bigcup_{1 \leq n \leq L(n)} F(i,n)$. Moreover, we use $F(e)$ to denote

the set of common channels among $F(i)$ and $F(j)$ for any link $e=(i,j)$ and use $\delta(e, f_m) \in \{0,1\}$ to denote as the indicator function of whether the channel f_m can be used by a link e .

The rate of transmission on link e is denoted by $x(e, f_m)$. This is the maximum rate at which mesh

TABLE I
NOTATIONS

Term	Description
$R_T(i)$	Transmission range of node i
$R_I(i)$	Interference range of node i
$x(e, f_m)$	The rate of transmission on link e
$E^-(i)$	Incoming edges of node i
$E^+(i)$	Outgoing edges of node i
G	Communication graph
B	A subset of outgoing links of a node
\hat{i}_n	The n th interface of node i
F_{ca}	Broadcast conflict graph
$\hat{e}_{mn}(i,j)$	Virtual link e of \hat{i}_m and \hat{j}_n
(\hat{i}_n, B)	Broadcast transmission of node \hat{i}_n in B
$r(B)$	The set of receiver nodes for the links in B
α	A fraction of time
D	The set of demands
$f^k(P)$	Flow demand on path P
$\hat{f}^k(P)$	The expected traffic demands k on path P
λ	Maximum multiplier

node i can communicate with mesh node j in one-hop communication using channel f_m . And for a path P and link e , we use $e \in P$ to denote that link e is on the path P . For a path P and node i , we use $i \in P$ to denote that node i is on the path P . Let us define basic notations in Table I.

In order to visualize a multichannel mesh networks, we use similar presentation as [30]. In this paper, node i with $L(i)$ radio interfaces can be seen as a group of $L(i)$ fully connected virtual $\hat{i}_n, n \in [1, L(i)]$, which represents that each virtual node \hat{i}_n has exactly radio interface n to connect to neighboring virtual nodes \hat{j}_m . Fig.2 shows an illustration of an example in which $L(i)=2, L(j)=3, L(k)=1$. It is noted that the virtual nodes in one shaded region correspond to a node in the original network. Furthermore, we denote the black edges in Fig.2b as directed external virtual links which connect virtual node with other nodes outside its group. This type of link has limited capacity and may cause interference to other external virtual links using the same channel. The grey edges in Fig.2(b) are represented as internal virtual links which connect virtual node in the same group, e.g., \hat{i}_1 and \hat{i}_2 . This kind of links has infinite capacity without interfere.

We define directed link $e(i,j)$ as the superposition of directed virtual links $\hat{e}_{mn}(i,j)$, where \hat{e}_{mn} is represented as the external virtual link from \hat{i}_m to \hat{j}_n using radio interface m of node i and n of node j . for simplicity, we use \hat{e} to denote such communication link \hat{e}_{mn} .

In wireless mesh networks, some of the nodes in the set V have gateway functionality and provide the connectivity to the Internet. We assume these gateway nodes not act as relay nodes.

Network coding exploits the broadcast nature of the wireless medium; hence a proper model that processes scheduling of broadcast transmissions is essential. In this paper, we analyze the utilization of broadcast transmissions and use the protocol model of interference introduced by Gupta and Kumar [31]. In this model, a transmission by a node i is successfully received by a node j iff. the intended destination j is sufficiently apart from the source of any other simultaneous transmission. This model implicitly assumes that each node will adopt the power control mechanism when it transmits signals. Some simulation analysis results [32][33] indicate that the model does not necessarily provide a comprehensive view of reality due to the aggregate effect of interference in wireless networks. However, it does provide some good estimations of interference and most importantly it enables a theoretical performance analysis of a number of

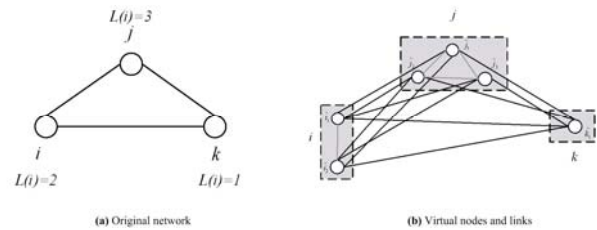


Figure 2. Virtual nodes and virtual links defined by splitting nodes

protocols designed in the literature.

B. Coding Rules

We assume network coding per flow is used in. Network coding within a multiple unicast session allows traffic from different transmission pairs to share network capacity

Consider k packets p_1, p_2, \dots, p_k at a node that have distinct next-hop nodes $1, 2, \dots, k$ respectively. Suppose these packets are coded together to form the coded packet $p = p_1 \oplus p_2 \oplus \dots \oplus p_k$ that is broadcast to all the above next-hop nodes. This is a valid network coding if the next-hop node \hat{i}_n for each packet p_i already has all other packets p_j for $\hat{j}_m \neq \hat{i}_n$ (subsequently it can decode p_i).

This can be happened as the following satisfy:

- (a) node \hat{i}_n is the previous-hop node of packet p_j , or
- (b) node \hat{i}_n overheard packet p_j from the transmission of the previous-hop node (opportunistic listening).

According to the above specification of coding opportunities, node \hat{i}_n can have packet p_j if (a) node \hat{i}_n was one of the nodes traversed by packet p_j before its previous-hop node, or (b) node \hat{i}_n overheard packet p_j from the transmission of a node traversed by packet p_j

before its previous-hop node. For either of the above conditions to be held, node \hat{i}_n can buffer packet p_j for longer periods of time with expect that additional coding opportunities involving packet p_j will arise at a node further downstream on its path. In contrast, conditions (a) and (b) do not require node \hat{j}_m to buffer packet p_j beyond the transmission at the next-hop node after the packet passed through or was overheard.

In this paper, we do not consider the model of coding opportunities arising from conditions (a) and (b) for tractability of the solution. Our assumptions are consistent with the conditions requiring minimal additional packet buffering at each wireless node for network coding.

C. Coding-based Conflict Graph

To address the problem of link interference, we further abstract the WMNs by a conflict graph [38]. Given a communication graph $G = (V, E)$, we use the conflict graph F_G corresponds to a directed link $\hat{e}_{mn}(i, j)$ in the communication graph G . There is an edge between vertex L_{i_n, \hat{j}_m} and vertex $L_{\hat{p}_s, \hat{q}_t}$ in F_G iff. L_{i_n, \hat{j}_m} conflicts with $L_{\hat{p}_s, \hat{q}_t}$ due to interference. i.e., the two links can not transmit/receive simultaneously.

Considering the broadcast nature in this paper, necessary extensions should be made for the above specification. Let B be a subset of outgoing links at certain node. We define the transmission rate within B simply as $x(B) = \min_{e \in B} \{x(e)\}$ for the reason that it allows us to make a conservative estimation of the rates of the transmission for broadcasts. A broadcast transmission at node \hat{i}_n in a subset B of its outgoing links is presented as (\hat{i}_n, B) . Besides, the associated broadcast traffic is denoted as $f(\hat{i}_n, B)$. Then we define the broadcast conflict graph F_{G_B} as a natural extension of the conflict graph for unicast transmissions. Each vertex in this graph represents a broadcast transmission (\hat{i}_n, B) . Let $r(B)$ denote the set of receivers for the links in broadcast set B . Two broadcasts (\hat{i}_1, B_1) and (\hat{j}_2, B_2) interfere and hence have an edge between them in the broadcast conflict graph if either (a) node $\hat{j}_2 \in r(B_1)$ is within interference range of node \hat{i}_1 , or (b) node $\hat{j}_2 \in r(B_2)$ is within interference range of node \hat{i}_1 .

Note that, the above conditions include special cases like $\hat{i}_1 = \hat{j}_2$ or $r(B_1) \cap r(B_2) \neq \Phi$.

With the above generalization of the conflict graph, we can obtain some constraints corresponding to the graph. Let $N_{(\hat{i}_n, B)}$ be the set of broadcast nodes (\hat{i}_n, B) . The fraction of time that broadcast (\hat{i}_n, B) is active is $f(\hat{i}_n, B)/x(B)$, which satisfies the constraint:

$$\sum_{(\hat{i}_n, B) \in N_{(\hat{i}_n, B)}} \frac{f(\hat{i}_n, B)}{x(B)} \leq 1 \quad \forall \text{ vertex } N_{(\hat{i}_n, B)} \text{ in } F_{G_B}. \quad (1)$$

Furthermore, let $\{I_1, I_2, \dots, I_q\}$ represent all the maximal independent sets in the broadcast conflict graph F_{G_B} , i.e., each set consists of corresponding broadcasts of the form (\hat{i}_n, B) . Let independent set I_j be active for α_j fraction of time. Thus, any set of active broadcast transmissions are contained in some independent set. And then we can obtain

$$\sum_{j=1}^q \alpha_j \leq 1. \quad (2)$$

Note that the fraction of time that an individual broadcast transmission is active is at the most the sum of the fraction of time that each independent set it belongs to is active. This can be rewritten as

$$\frac{f(\hat{i}_n, B)}{x(B)} \leq \sum_{j: (\hat{i}_n, B) \in I_j} \alpha_j \quad \forall \text{ broadcasts } (\hat{i}_n, B). \quad (3)$$

We will use the constraints in our linear programming formulations for routing with network coding in next section.

IV. PROBLEM FORMULATION

In this section, we first give a Linear Programming (LP) formulation when we want to maximize the network throughput while satisfying the generalized QoS requirements. We do not take opportunistic listening into consideration and assume that, in the absence of opportunistic listening, a coding opportunity at a node involves XOR exactly two packets. The proof is straightforward and is omitted for lack of space.

A. Maximize Throughput under QoS Requirements

We now formulate the problem of maximum throughput routing with network coding considering QoS provisioning. Assume a flow demand on path P is denoted as $t^k(P)$. Our objective is to find flow assignment that maximizes the network throughput and improve load balance of the achieved flow under QoS demands. Let D be the set of demands. A demand $k \in D$ has source nodes $s(k)$, destination nodes $d(k)$, and the expect traffic value of demands k on the path P is $l^k(P)$.

If virtual link \hat{e} is assigned channel f_m for α fraction time, and the capacity of the virtual link using channel f_m is denoted as $c(\hat{e}, f_m)$. Then $\alpha \cdot c(\hat{e}, f_m)$ is the corresponding achieved flow.

The throughput under QoS demands is defined as the maximum multiplier by λ such that all demands with their traffic values multiplied by λ can be feasibly routed by the network. Then, the problem of routing under network coding so as to maximize throughput under QoS demands can be expressed as the following linear program (LP):

Maximize λ

Subject to

$$t^k(P) = \lambda l^k(P) \quad \forall k \in D \quad (4)$$

$$f^{\{\hat{e}_1, \hat{e}_2\}}(\hat{i}_n, B) \leq \sum_{k \in D} \sum_{\{\hat{e}_1, \hat{e}_2\} \in P} t^k(P) \quad \forall \hat{e}_1, \hat{e}_2 \in E^+(\hat{i}_n), \hat{i}_n \in V \quad (5)$$

$$f^{\{\hat{e}_1, \hat{e}_2\}}(\hat{i}_n, B) \leq \sum_{k \in D} \sum_{\{\hat{e}_2, \hat{e}_1\} \in P} t^k(P) \quad \forall \hat{e}_1, \hat{e}_2 \in E^+(\hat{i}_n), \hat{i}_n \in V \quad (6)$$

$$f^{\{\hat{e}\}}(\hat{i}_n, B) = \sum_{k \in D} \sum_{\hat{e} \in E^+(\hat{i}_n)} t^k(P) + \sum_{\hat{e}_1 \in E^-(\hat{i}_n)} [\sum_{k \in D} \sum_{\{\hat{e}, \hat{e}_1\} \in P} t^k(P) - f^{\{\hat{e}, \hat{e}_1\}}(\hat{i}_n, B)] \quad \forall \hat{e} \in E^+(\hat{i}_n), \hat{e} \in V \quad (7)$$

$$\sum_{(\hat{i}_n, B) \in C, |B| \leq 2} \frac{f(\hat{i}_n, B)}{x(B)} \cdot \sum_{k \in D} \sum_{\hat{e} \in P} t^k(P) \cdot D \leq \Phi(\hat{i}_n) \quad (8)$$

$$\sum_{L(i)} \sum_{f \in F} \Phi(\hat{i}_n) = \Phi(i) \quad (9)$$

$$\sum_{(\hat{i}_n, B) \in C, |B| \leq 2} \frac{f(\hat{i}_n, B)}{x(B)} \leq 1 \quad \forall \text{ vertex } C \text{ in } F \quad (10)$$

Eq. (4) states that the total traffic routed on the available paths for a demand must equal the demand value multiplied by its throughput.

Eq. (5) - Eq. (6) determine the maximum amount of coded traffic $f^{\{\hat{e}_1, \hat{e}_2\}}(\hat{i}_n, B)$ that can be broadcasted on outgoing links $\{\hat{e}_1, \hat{e}_2\}$ at node \hat{i}_n . The total traffic traversing node \hat{i}_n along link \hat{e}_1, \hat{e}_2 is $\sum_{k \in D} \sum_{\hat{e}_1, \hat{e}_2 \in P} t^k(P)$ and along link sequence \hat{e}_2, \hat{e}_1 is $\sum_{k \in D} \sum_{\hat{e}_2, \hat{e}_1 \in P} t^k(P)$. Thus, $f^{\{\hat{e}_1, \hat{e}_2\}}(\hat{i}_n, B)$ is at most each of these amounts.

Eq. (7) gives the total amount of traffic $f^{\{\hat{e}\}}(\hat{i}_n, B)$ that is unicast on outgoing link \hat{e} at node \hat{i}_n . This traffic can be divided into two parts. The first part is the traffic that originates at node \hat{i}_n and is sent on link \hat{e} , and this traffic equals $\sum_{k \in D} \sum_{\hat{e} \in P} t^k(P)$. The second part is the amount of transit traffic at node \hat{i}_n with next-hop that could not be coded with other flows and equals $\sum_{\hat{e}_1 \in E^-(\hat{i}_n)} [\sum_{k \in D} \sum_{\{\hat{e}, \hat{e}_1\} \in P} t^k(P) - f^{\{\hat{e}, \hat{e}_1\}}(\hat{i}_n, B)]$.

Eq. (8) is for the QoS constraints in WMNs. Assume that each node $\hat{i}_n \in V$ in the network will spend certain resources (e.g., bandwidth) for relaying a unit amount of data to a neighboring node \hat{j}_m . Further, node \hat{i}_n has a given amount of resources $\Phi(\hat{i}_n) > 0$. The objective is then to maximize the network throughput that can be achieved by such a network while the network will last for a certain duration D . The above constraints are namely QoS demands in this paper.

Eq. (9) states that for all the channels that interfaces of node i work on should equal to the total amount of resource constraint of a node.

Finally, Eq. (10) is the broadcast transmission scheduling constraint corresponding to cliques in the broadcast conflict graph, as discussed in Section 2. The cliques are restricted to broadcast sets of size at most 2, since there is no opportunistic listening.

The path-indexed routing variable $s t^k(P)$ can be reduced to polynomial size by converting to dual-link-indexed variables $t^k(\hat{e}_1, \hat{e}_2)$, where (\hat{e}_1, \hat{e}_2) denotes the incoming and outgoing link pair at each node. This corresponds to routing on a graph with a node-splitting transformation, but we will not discuss the details for the reason of lacking of spaces.

Simplicity, we call the above analytical model NETCOD-MM. And in this paper, we will also propose a centralized algorithm to solve the program.

B. Link Scheduling

Our objective is to make each link $L \in G$ a transmission schedule $S(L)$, which is the list of time slots and the corresponding channels such that schedule is interference free and the overall throughput of the network is maximized. Let $X_{\hat{e}, t, f_m} \in \{0, 1\}$ be the indicator variable, which is 1 only when \hat{e} will transmit at time t using channel f_m .

In this paper, we focus on periodic schedules. Let $I(\hat{e})$ denote the set of links \hat{e}' that will cause interference if \hat{e} and \hat{e}' are scheduled at the same time slot t using the same channel f_m . It is noted that a virtual edge $\hat{e}' \in I(\hat{e})$ if \hat{e}' share a common virtual node since any radio can only be active for either transmitting or receiving at one channel. A schedule S is interference free if $X_{\hat{e}, t, f_m} + X_{\hat{e}', t, f_m} \leq 1$ for any $\hat{e}' \in I(\hat{e})$, any time slot t , any channel f_m , and any f_n with $I_{set}(f_m, f_n) = 1$. Consequently, we say that $(\hat{e}', f_n) \in I(\hat{e}, f_m)$ if we cannot set $X_{\hat{e}, t, f_m} = 1$ and $X_{\hat{e}', t, f_n} = 1$ simultaneously for some time t .

Now, we can mathematically formulate that for a flow $f(e)$, the necessary and sufficient condition for it be scheduled *iff.* we can find solution $X_{\hat{e}, t, f_m} \in \{0, 1\}$ satisfying the following conditions:

$$X_{\hat{e}, t, f_m} + X_{\hat{e}', t, f_m} \leq 1 \quad \forall (\hat{e}', f_m) \in I(\hat{e}, f_m) \quad (11)$$

$$\frac{\sum_{1 \leq t \leq T} X_{\hat{e}, t, f_m}}{T} = \alpha \quad \forall \hat{e}, f_m \quad (12)$$

Eq. (11) states that a schedule should be interference free. And Eq. (12) says that the schedule should achieve the required flow within the fraction time of α .

Furthermore, we assume that every wireless interface can dynamically change the channel (e.g., spectrum or CDMA code) for transmitting signals based on a certain schedule.

It is widely known that it is NP-hard to decide whether a feasible scheduling $X_{\hat{e},t,f_m}$ exists when given the flow $f(e)$ for wireless networks with interference constraints.

V. SCHEDULING ALGORITHM

In this section, we present an algorithm to find a feasible link scheduling given a flow found by the proposed LP.

First, we present a centralized scheduling for link transmission. Assume that T is the number of time slots per scheduling period. We need to schedule $T \cdot \alpha$ time slots for a virtual link \hat{e} using channel f_m . For simplicity, we assume that T leads $T \cdot \alpha$ to be integer for every virtual edge \hat{e} and f_m . Moreover, we need to ensure that each scheduled pair is interference free and satisfies the radio and channel-availability constraints of all nodes.

Algorithm 1 in Table II shows the presented scheduling method. The basic idea is to first sort the external virtual links based on some specific order and then process the requirement α for each of the possible channel f_m . We assume that a table $T(t)$ for each virtual node \hat{i}_n . The table stores the current assignment for the pair (virtual link, channel). For example, an entry in $T(t)$, (\hat{e}, f_m) means that node i uses its n th NIC to transmit at time t using channel f_m for link \hat{e} if the directed virtual edge \hat{e} starts from virtual node \hat{i}_n ; otherwise, node i will use n th NIC to receive at time t using channel f_m for a link \hat{e} at virtual node \hat{i}_n .

For a virtual edge \hat{e} , we should find $N(\hat{e}, f_m) = T \cdot \alpha$ empty entries that will not cause interference to other scheduled pairs. If there are available consecutive time slots of a radio, we will choose consecutive time slots so as to reduce the channel switching cost.

In this paper, we consider the algorithm under protocol model. We consider the conflict graph, and choose the vertex, which is the virtual link in the virtual communication graph with largest value $d_{i,j}^{in} - d_{i,j}^{out}$ in the residues conflict graph and remove the vertex and its incident edges. Here, $d_{i,j}^{in}$ and $d_{i,j}^{out}$ are the in-degree and out-degree of vertex L_{ij} in the conflict graph under the protocol model. Repeat this process until there is no vertex in the graph. Then, remove the order.

It is worth noting that the time complexity of Algorithm 1 is $O(m \log m)$, most of the time is spent on sorting the links, the inner nested loops in step 3 to 12 have a constant upper bound of $(\frac{K(K+1)}{2})^2 \times T$, and the over all time complexity is $O(m \log m) + O(m(\frac{K(K+1)}{2})^2 T) = O(m \log m)$ for a sufficiently large m . It is noted that α can be found in time $O(m^{3.5})$ since an LP of m variables can be solved in time $O(m^{3.5})$ by using an interior point method.

TABLE II

ALGORITHM 1: CENTRALIZED GREEDY LINK SCHEDULING

Input: A virtual communication graph $G=(V,E)$ of m links, and α for all external virtual links and for all channels.

Output: An interference-free link-channel scheduling.

- 1: Sort the external links in the virtual communication graph G according to some special order. Let $(\hat{e}_1, \hat{e}_2, \dots, \hat{e}_m)$ be the sorted list of links.
- 2: **for** $k=1$ to m **do**
- 3: **for** each possible channel $f_m \in F$ **do**
- 4: Let $N(\hat{e}_k, f_m) = T \cdot \alpha$ be the number of time slots that virtual link \hat{e}_k will be active using channel f_m .
- 5: Assume $\hat{e}_k = (i, j)$. Set allocated $\leftarrow 0$; $t \leftarrow 1$;
- 6: **while** allocated $< N(\hat{e}_k, f_m)$ **do**
- 7: **if** $X_{\hat{e}_k,t,f_m} = 0$ for every (\hat{e}, f_m) pair **then**
- 8: **if** $t \leq t$ then set $X_{\hat{e}_k,t,f_m} \leftarrow 1$ and allocated \leftarrow allocated +1;
- 9: **end if**
- 10: Set $t \leftarrow t+1$.
- 11: **end while**
- 12: **end for**
- 13: **end for**

VI. PORMANCE EVALUATION

A. Evaluation Setups

Numerical results for two different network topologies are presented in this section, employing the proposed link schedule algorithm. The throughput benefits of network coding strongly depend on the network topology and communication demands. To have a basic comparison, we mainly consider two topologies as the basis of comparison in this paper: (1) 4*4 grid topology wireless network and (2) a 32-node random topology. In each simulation, a traffic flow of difference priority and rate which presents different QoS requirements is generated from each source node and their packets are buffered and coded with the most possibility in the respective relay nodes to the destination. For simplicity, we call the proposed algorithm NETCOD-MM. Furthermore, we not only analyze the impact of multiple radios and multiple channels on NETCOD-MM, but also evaluate the performance of NETCOD-MM with other transmission scheduling, ETX [3] and LP-Flow-throughput which is proposed by [30].

The topologies are shown in Fig. 3. For the grid topology, we assume the transmission range as 100 units; the interference range as 200 units, and the distance between each node is 100 units. While for the random topology, the average node degree was 6.8 and the maximum degree was 14. The capacity of communication link is chosen according to Shannon's formula. The source and destination for each flow is chosen at random.

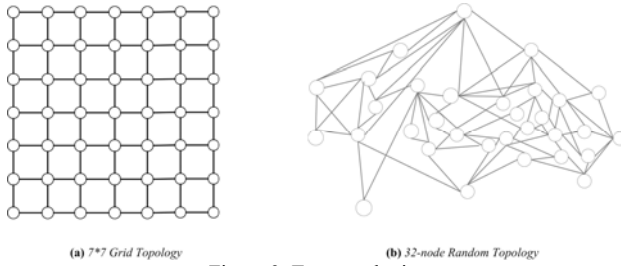


Figure 3. Two topologies

B. Performance of Multi-channel

In this simulation, we studied the affect of using multiple channels per radio on the maximal throughput while satisfying the generalized QoS requirements. In this simulation, we fixed the maximum number of NICs to 2 and 4 in separate simulation runs. In each simulation, we vary the maximum number of channels per radio from 2 to 4 at each simulation run, and we also setup different QoS-priority flows varied from 5 to 20, so as to evaluate the impact of multi-channel under different traffic flows. Fig.4(a) shows our results when maximum number of radios is two; each point in the figure is the average of five simulations. The figure shows that increasing the number of channels per radio increases the throughput. When the number of radios changed to four, our results showed the same trend. With the number of radios increasing, the throughput does not increase as can be depicted by comparing the results in Fig.4(a) for two radios and those in Fig.4(b) for four radios. This is because the network with higher radios (channels) than that with smaller radios (channels), which is with high probability. In conclusion, the network with higher maximal radio (channel) has a greater upper bound for the node to randomly choose the radios or channels.

The performance of 32-node random topology shows the similar trends when the number of channels increases, the evaluation results can be found in Fig.5.

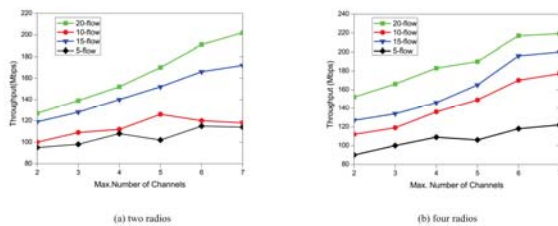


Figure 4. Impact of multi-channel on throughput under different QoS flows over grid topology

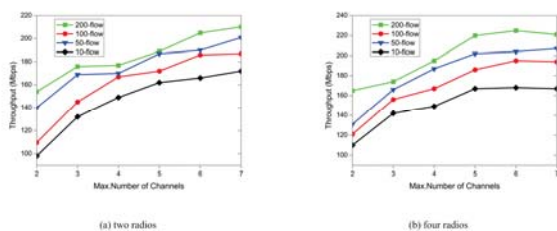


Figure 5. Impact of multi-channel on throughput under different QoS flows over random topology

C. Performance of Multi-radio

In this simulation, we studied the affect of using multiple radios per node on the maximal throughput while satisfying the generalized QoS requirements. In this simulation, we fixed the maximum number of channels to 2 to 4 in separate simulation runs. And we also setup different QoS-priority flows varied from 5 to 20, so as to evaluate the impact of multi-radio under different traffic flows. In each simulation, we varied the maximum number of radios from one to seven and randomly assigned each node a number of radios between one and the maximum value at each simulation run. Fig. 6(a) and Fig.6(b) show our results when maximum number of channels is set to two and four, and each point in the figure is the average of five simulations. The figures show that the throughput measures increase until a certain point where they start bouncing up and down each time the maximum number of radios increases. The reason behind the bouncing up is that the actual number of radios assigned to each node is randomly generated for each simulation run; for the case where the throughput decreased by increasing the maximum number of radios per node, we compared the actual total number of radios in the network for all simulation runs. We found that when the maximum number of radios is five, the actual total number of assigned radios for all nodes is less than that of the case when the maximum number of radios is four. Therefore, the number of available radios in the network is less; hence, the probability of assigning no conflicting channels for the interfering links decreased, and that is why the throughput decreased. We observe furthermore from Fig. 6(a) and Fig. 6(b) that throughput decreases slower with a greater number of channels, *i.e.*, the decrease is sharper with four channels than with seven. This is due to the fact that more channels are assigned per radio, which increases the probability of assigning no conflicting channels to interfering links, which increase throughput compare with the case of a lesser number of channels/radios.

The performance of 32-node random topology shows the similar trends when the number of channels increases, the evaluation results can be found in Fig.7.

D. Comparison with Routings

Fig. 8(a) and Fig.8(b) show the throughput performance of NETCOD-MM, ETX and LP-Flow-Throughput under different traffic loads. In each figure, we plot the performance of the above strategies with different traffic load. In Fig. 8(a), LP-Flow-Throughput performs closer to NETCOD-MM, as QoS flows increase, ETX becomes more difficult to find paths that do not interfere with other flows and thus the gain increases slower than the other two strategies. NETCOD-MM outperforms in throughput gain among the three strategies purely due to coding opportunities. Coding opportunities increase with the number of flows resulting in increasing throughput gain. We observe that NETCOD-MM outperforms both the schemes with a maximum gain of 17% over ETX and 11% over LP-Flow-Throughput. The

NETCOD-MM with a large scale of flows utilizes more bandwidth as long as the packet coding opportunities are large enough to allow sufficient packets to be transmitted at the intermediate nodes. However, without opportunistic listening, NETCOD-MM can only process two packets each slot which cannot lead to significant improvement over LP-Flow-Throughput. The overall network throughput gains achieved by NETCOD-MM are comparably higher because network coding technology and opportunistic coding provide more information with a XOR packet. Among the three algorithms, the throughput gain of ETX is increasing slower as the number of flows increasing. This is due to lacking of bandwidth resource to deal with commodity flows. In Fig. 8(b), with more channels and radios are equipped for each node (four radios with four channels), the overall throughput of these algorithms is achieved a little better than those in Fig. 8(a). The advantages of multi-channel and multi-radio are not as obvious as we expected. In further research work, we will enlarge simulation scale so as to exploit more advantages of multi-channel and multi-radio

The performance of 32-node random topology shows the similar trends when the number of channels increases, the evaluation results can be found in Fig.9.

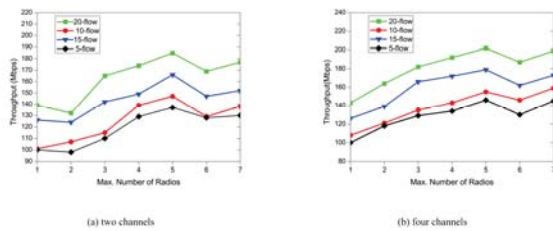


Figure 6. Impact of multi-radio on throughput under different QoS flows over grid topology

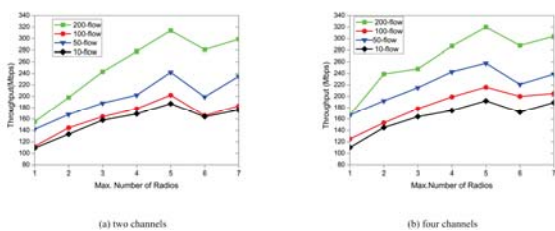


Figure 7. Impact of multi-radio on throughput under different QoS flows over random topology

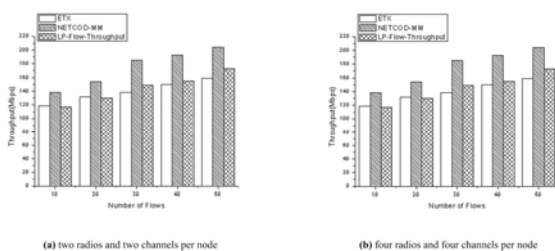


Figure 8. NETCOD-MM vs. ETX and LP-Flow-Throughput: throughput on traffic load with different QoS flows over grid topology

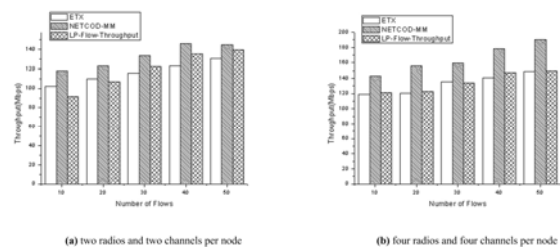


Figure 9. NETCOD-MM vs. ETX and LP-Flow-Throughput: throughput on traffic load with different QoS flows over random topology

VII. CONCLUSION

In this paper, we investigate the problem of network-wide data transmission load balance under the consideration of QoS requirements (packet delivery ratio, packet delay) over multi-radio and multi-channel WMNs. To address this problem, we first provide a popular network coding method used for unicast wireless networks to increase network-wide throughput. We then present an integer linear programming description of a given multi-radio and multi-channel WMN, addressing network coding traffic, routing, QoS requirements and scheduling optimizations. Moreover, we propose a link schedule algorithm NETCOD-MM as a centralized solution to the LP problem. The proposed link schedule algorithm combines network coding strategy increase network-wide throughput while satisfying the generalized QoS requirements.

The simulation results show that the proposed algorithm NETCOD-MM outperforms ETX and LP-Flow-Throughput in 4*4 grid topology as well as in 32-node random topology.

We provided a high-level description of our proposed routing model for WMN in this paper,. The future work intends to extend our proposed algorithm applied by adjusting the physical-layer parameters, such as Signal-to-Interference-plus-Noise Ratio (SINR) threshold according to the transmission rates supported by IEEE 802.11 protocol. Future works can also consider implementing the physical model [31].

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