NETWORK-CODING-BASED SCHEDULING AND ROUTING SCHEMES FOR SERVICE-ORIENTED WIRELESS MESH NETWORKS

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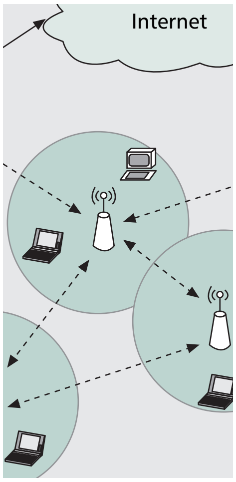

Wireless network coding is a key technology to improve the network throughput in multi-hop wireless networks since it can exploit not only the broadcast nature of the wireless channel, but also the native physical-layer coding ability.

ABSTRACT

Service-oriented wireless mesh networks have recently been receiving intensive attention as a pivotal component to implement the concept of ubiquitous computing due to their easy and cost-effective deployment. To deliver a variety of services to subscriber stations, a large volume of traffic is exchanged via mesh routers in the mesh backbone network. One of the critical problems in service-oriented wireless mesh networks is to improve the network throughput. Wireless network coding is a key technology to improve network throughput in multihop wireless networks since it can exploit not only the broadcast nature of the wireless channel, but also the native physical-layer coding ability by mixing simultaneously arriving radio waves at relay nodes. We first analyze the throughput improvement obtained by wireless network coding schemes in wireless mesh networks. Then we develop a heuristic joint link scheduling, channel assignment, and routing algorithm that can improve the network throughput for service-oriented wireless mesh networks. Our extensive simulations show that wireless network coding schemes can improve network throughput by 34 percent.

INTRODUCTION

Recent years have witnessed the emergence of a variety of wireless services, such as videoconferencing, Internet Protocol (IP) TV, music downloading, and online gaming. Motivated by the concept of ubiquitous computing, these promising wireless services are designed to be available for people anytime and anywhere. Wireless mesh networks, where nodes dynamically establish an ad hoc networks and maintain mesh connectivity, have emerged as a key network architecture to support ubiquitous computing-based services [1]. First, based on cutting-edge physical layer techniques, such as orthogonal frequency-division multiplexing (OFDM) and ultra-wideband (UWB), wireless mesh networks can provide broadband wireless access. Second, being a special type of ad hoc networks, wireless mesh networks inherently have the advantages of ad hoc networks, such as fast and simple deployments, easy network maintenance, and robustness. Finally, by embracing multihop communications, wireless mesh networks can cover large-scale areas with low infrastructural investment, which is the critical factor in implementing the concept of ubiquitous computing, especially for locations in the world's rural areas.

There are two types of components in wireless mesh networks: mesh routers and mesh clients. The mesh router, which typically has multiple radio interfaces, is a stationary relay node with a gateway/access point. First, performing the role of relay, mesh routers form the mesh backbone to support broadband wireless traffic. Second, as the access point, some mesh routers provide broadband access to mesh clients. Third, some mesh routers, connected by wire to the Internet or other networks, act as gateways to provide services to mesh clients.[1] Figure 1 shows an example of a service-oriented wireless mesh network. Wireless mesh networks can provide a variety of services to users. A large volume of traffic is exchanged by mesh routers over the mesh backbone network. The major data traffic (e.g., Internet access) is carried by multiple unicast sessions overlaid on backbone wireless mesh networks [2]. Clearly, how to improve the throughput of backbone wireless mesh networks is a critical challenge in the design of service-oriented wireless mesh networks. Wireless network coding (NC) is considered as a key technology to improve the throughput of multihop wireless networks, since

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[1] The services can be available to all mesh clients in the mesh network. The mesh clients, which do not connect with the gateway mesh router directly, can connect to it through multihop communications.

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it can exploit not only the broadcast nature of the wireless channel, but also the native physical-layer coding ability by mixing simultaneously arriving radio waves at relay nodes.

The promising wireless NC technique motivates us to investigate how to practically apply the wireless NC schemes and how well the wireless NC schemes can perform in multihop, multichannel, and multiradio wireless mesh networks. The main goal of this article is to analytically model the network throughput improvements of wireless NC schemes in service-oriented wireless mesh networks. Specifically, applying the linear programming/optimization technique, we formulate a general framework, which is applicable to *any* transmission schemes with or without NC, to maximize the network throughput for wireless mesh backbone networks. Our framework features multipath routing that efficiently seizes wireless NC opportunities. Under this developed framework, we propose a joint link scheduling, channel assignment, and routing algorithm to approach the obtained optimal network throughput. We also conduct extensive simulations to validate and evaluate the performance of our proposed joint link scheduling, channel assignment, and routing algorithm.

The rest of this article is organized as follows. The next section introduces the background of wireless NC. We then develop the system models for the mesh backbone networks and the general linear programming framework. We then design the joint link scheduling, channel assignment, and routing algorithm for wireless NC schemes. The following section evaluates the network throughput gains of wireless NC schemes and the performance of our proposed algorithm through simulations. We present our conclusions in the final section.

Wireless NC

NC is receiving more and more research attention since it is a promising technique to increase network throughput for both wired and wireless networks. The notion of NC was first coined in [3] in the context of wired multicast communications. Since then, extensive research efforts [4, 5] have been devoted to the area of design and analysis for NC in wired networks. However, wireless networks cannot directly benefit from the NC schemes designed for their wired counterparts.

By exploiting the broadcast nature of the wireless channel, conventional wireless NC proposed in [6, 7] can significantly increase network throughput as compared to the traditional non-NC transmission scheduling-based scheme in multihop wireless networks. The essential idea of conventional wireless NC can be explained as follows using a simple two-way relay network example. As shown in Fig. 2, node A wants to send a single packet to node C, while node C wants to send a single packet to node A. Due to transmission range limitations, these two paths both go through relay node B. Suppose the time axis is divided into time slots, and the transmission of each packet spends one time slot. Then, if we adopt the non-NC scheduling-based scheme, four time slots are needed to complete these two-way relay transmissions. As shown in Fig. 2a, the following is a possible sequence of these transmissions under the non-NC scheme:

1)Node A sends a packet to node B while node C remains silent.
2)Node B relays A's packet to node C.
3)Node C sends its packet to node B while A remains silent.
4)Node B relays C's packet to node A.

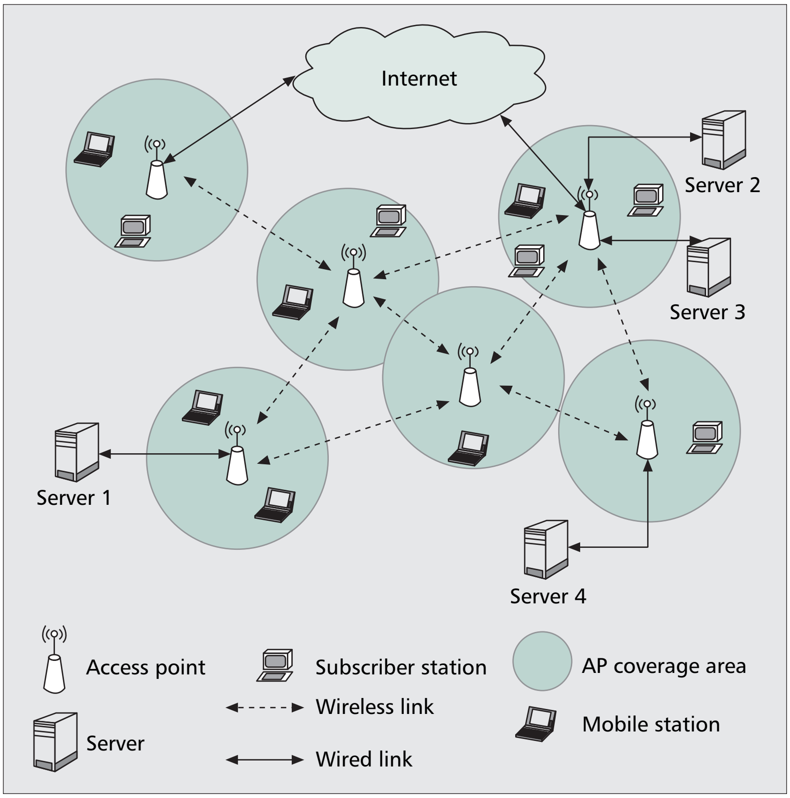
In contrast to the non-NC scheme, the conventional wireless NC scheme only needs three time slots to complete the two-way relay transmissions.

Figure 2b shows the sequence of transmissions using the conventional wireless NC scheme:

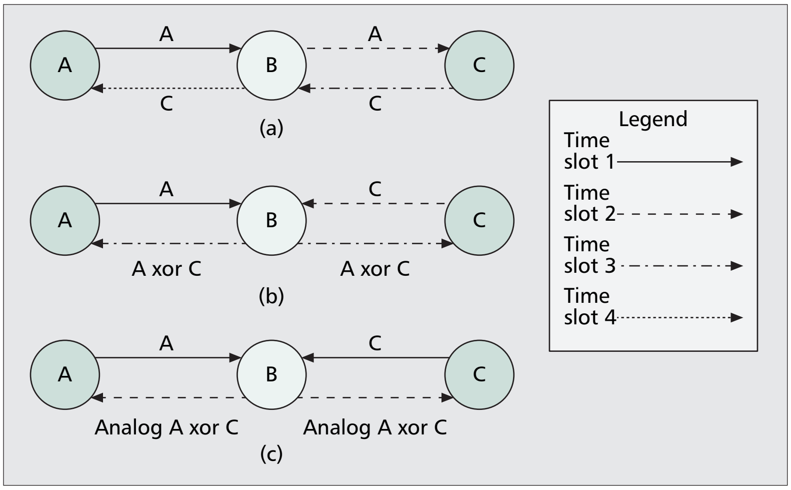
1 Node A sends a packet to node B.
2 Node C sends a packet to node B.
3 Node B transmits a new packet obtained by performing an XOR of A's and C's packets.

Node A can XOR the received new packet from node B with its own packet to obtain C's packet. In a similar way, node C can get A's packet.

The authors of [8, 9] developed *analog NC*, which can even take advantage of the native physical-layer coding ability by analogously mixing simultaneously arriving radio waves at the relay nodes to further increase the network throughput. As shown in Fig. 2c, under analog NC, the two-way relay transmissions can be completed in just *two time slots*. In the first time slot, A and C transmit their packets to node B simultaneously, resulting in a collision of their transmissions at relay node B. Due to the collision, relay node B receives the sum of A's and C's analog signals and cannot decode the bits. In the second time slot, relay node B simply amplifies and forwards the collided signal at the physical layer without decoding it. Since node A knows



■ **Figure 1.** *Illustration of wireless mesh networks.*



■ **Figure 2.** *Diagram of the transmission procedure of non-NC and wireless NC schemes: a) traditional non-NC; b) conventional NC; c) analog NC.*

the packet it sent, it also knows the packet's corresponding analog signal. It can thus subtract its original signal from the collided signal to get the signal of C's packet, from which it can decode C's packet. Likewise, C can decode A's packet.

System Models

The Network Model

In this article we focus on the wireless mesh *backbone* network. For convenience of presentation, we refer to mesh routers as nodes in the rest of our article. The wireless mesh backbone network is characterized by the nodes and the links corresponding to pairs of nodes within direct communication range and interference range. Let V, E, and I be the set of nodes, the set of data links, and the set of interference links, respectively. Note that E is the set of links that can carry data, while I is the set of links that can sense signals but cannot decode the data. Denote by $e = (s, t)$ the directed link in the network from node s to node t with $s, t \in V$. Let $\bar{e} = (t, s)$ be the reverse link of $e = (s, t)$.

There are a number of unicast sessions among different source and destination pairs in the network. Denote the set of sessions by A. Any given session a, with $a \in A$, is characterized by the source node, destination node, and throughput, respectively, of session a. Note that the sessions are defined at a high level such that any given session can consist of a number of applications that communicate between the same source and destination mesh routers. The packets of a session can be routed from source to destination in multiple hops if there is no direct link between the source and destination nodes. Every mesh router in the wireless mesh network can be a source or destination. To incorporate multipath routing, there may be multiple paths for a session. Suppose that there are totally M orthogonal channels in the wireless mesh network.

NC Links Combinations

An NC links combination is defined as a set of data links that together can perform the NC operation. The existence of an NC links combination depends on the routes/paths of different sessions. Intuitively, if there are three nodes that form the two-way relay subnetwork, we can apply the NC operations on these three nodes. Suppose there are links $e_1 = (A, B)$ and $e_2 = (C, B)$, and there is no direct link between nodes A and C. That is, node B is the relay node for nodes A and C. If there are two different sessions such that one session's traffic goes from nodes A, B through C, and another session's traffic goes from nodes C, B, through A, we say that $L = \{e_1, e_2\}$ is the incoming NC links combination. In other words, links e_1 and e_2 can be active at the same time to perform the analog NC where nodes A and C broadcast packets to node B at the same time. The example of an incoming NC links combination is shown in Fig. 3a.

On the other hand, links $\bar{e}_1$and $\bar{e}_2$, which are the reverse links of e_1 and e_2, respectively, can also be active at the same time to perform NC operation, where node B can broadcast the combined packets to nodes A and C simultaneously. Hence, we call $L = \{\bar{e}_1, \bar{e}_2\}$ an outgoing NC links combination. Figure 3b shows the example of an outgoing NC links combination. Note that the pair of links in the incoming/outgoing NC links combination can and must be active at the same time. The incoming NC links combination characterizes the native physical-layer coding ability of analog NC, while the outgoing NC links combination represents the broadcast nature of the wireless channel. Note that the links in the NC links combination are traversed by at least two different sessions that have reverse directions to each other.

The incoming and outgoing NC links combinations represent the basic NC scenario. We notice that the outgoing and incoming NC pair may be further combined into a more powerful NC links combination, as shown in Figs. 3c and 3d. Thus, we can further explore the NC opportunity involving more than three nodes. For example, the five-node NC links combination shown in Fig. 3d consists of two outgoing NC links combinations and one incoming NC links combination. In particular, node B broadcasts packets to nodes A and C, while node D broadcasts to nodes C and E, which represents two outgoing NC operations. On the other hand, node C receives packets from nodes B and D simultaneously, which is the incoming NC operation.

Let $\mathcal{L}$ be the superset of all types of NC links combinations and $\mathcal{L}(e)$ be the subset of $\mathcal{L}$ such that for any $L \in \mathcal{L}(e)$, L contains link e. Based on the idea of analog NC, every link in the NC links combination can be active at the same time. Thus, theoretically, more links being included in the NC links combination implies higher network efficiency the network can achieve. However, the larger the number of involved NC links, the more complicated the system. This is because the nodes associated with the NC links need to be accurately synchronized together to transmit/receive packets to take advantage of analog NC. It is not realistic to achieve accurate synchronization for a large number of nodes. Hence, in this article we only consider cases where there is no more than one incoming NC links combination. In other words, in an NC links combination there is at most one pair of incoming links that are incident in a single node. Therefore, the most complicated and realistic case we consider is the five-node NC links combination. Figure 3 shows all the possible realistic NC scenarios we consider.

Problem Formulation

Let $k(a)$ be the predetermined flow weight for session a, with $a \in A$. The larger the $k(a)$ for session a, the higher the flow rate session a requests. Let $F(a)$ be the total amount of flow over session a with $a \in A$. The objective of the problem is to maximize the overall weighted throughput, $\sum_{a \in A} F(a)k(a)$. At the same time, the optimization problem is also subject to the following constraints.

Link Flow Constraint — There are two types of traffic on link e: unicast traffic and NC traffic. For each link e, let $f_m^U(e)$ and $f_m^{NC}(L)$ be the flow of unicast traffic on link e and the flow of NC traffic on link e associated with NC links combination L with $L \in \mathcal{L}(e)$, respectively, over channel m. Thus, the total amount of flow, denoted by $f(e)$, of link e, with $e \in E$, is the sum of all unicast traffic and NC traffic over all channels. At the same time, the amount of flow on link e should also be no less than the total flow of all sessions that have routes going through link e.

Flow Conservation Constraint — The flow conservation constraint is used to maintain flow balance at every wireless node for each session. For each non-source/destination node, the total amount of outgoing flow should be equal to that of incoming flow.

Transmission Interference Constraint — The transmission interference constraint characterizes the broadcast nature of the wireless channel. As we know, for unicast communications, if one link, say e, is active, all the other links that belong to the conflict set of link e cannot be active at the same time. Similarly, for NC communications, if one NC link combination, say L, is active, all the other links that belong to the set of conflict links associated with L must be mute. In other words, every data link or NC combination needs to share the common wireless media with its conflict links. Let $E^C(e)$ and $\mathcal{L}^C(e)$ be the sets of conflict links and NC combinations, respectively, for link e, and $c_m(e)$ be the data rate of link e. We can use the normalized active time for unicast links and NC links combinations to model the above characteristic, that is,

$$\sum_{e' \in E^C(e)} \frac{f_m^U(e)}{c_m(e)} + \sum_{L \in \mathcal{L}^C(e)} \frac{f_m^{NC}(L)}{\min_{e \in L}\left\{c_m(e)\right\}} \le 1 \qquad (1)$$

where the first and second terms denote the normalized active time for unicast links and NC links combinations, respectively; $\min_{e \in L}\{c_m(e)\}$ in the second term is to guarantee that all nodes associated with L can correctly decode the received signals over channel m. Note that the constraint of Eq. 1 is applied to not only the data links (E) but also the interference links (I). This is because given an interference link e, with $e \in I$, between two nodes u and v, if one of the data links incident on either node u or v is active, the other node has to be silent for that time slot.

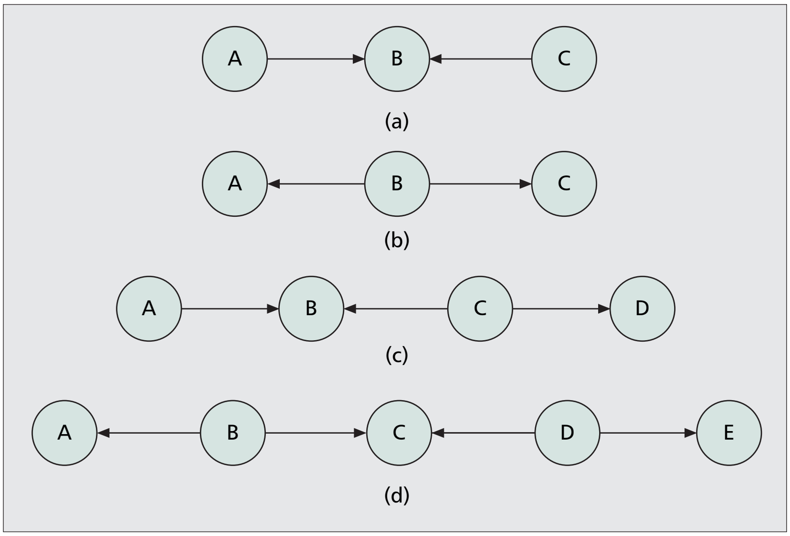
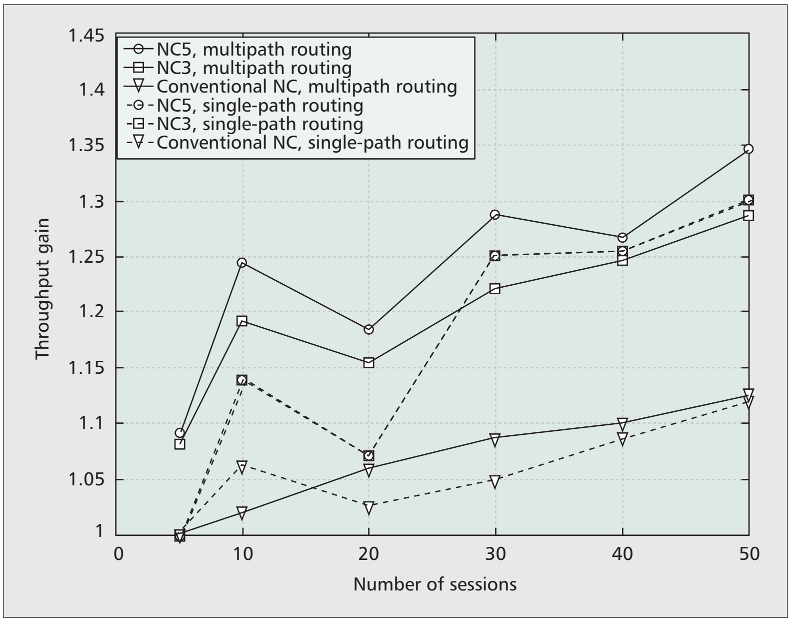


Figure 3. *Illustrations of various NC links combinations: a) an incoming NC links combination; b) an outgoing NC links combination; c) a 4-node NC links combination; d) a 5-node NC links combination.*

Link Capacity Constraint — The link capacity constraint is to secure that the link rate is not beyond the upper bound of the link flow for each data link. Similarly, the NC flow should be less than the minimum link rate among all links associated with this NC links combination.

Node Radio Constraint — The number of radios equipped by a node decides the number of channels the node can simultaneously access. In any interference-free schedule, the total number of active links and active NC links combinations at the same time cannot be larger than the number of radios equipped by the node. This node radio constraint can be characterized for each node in the network, setting the total normalized active time of unicast links and NC links combinations to be less than the number of radios.

After the above constraints are specified, we can finalize a *linear program* (LP) to find the flows that maximize the overall weighted throughput subject to the constraints. It is worth noting that the LP represents the general form for the throughput optimization problems of the following three different schemes: the non-NC scheme, conventional NC scheme, and analog NC scheme. In particular, if we let $\mathcal{L}(e) = \emptyset, \forall e \in E$, the LP reduces to the throughput optimization problem for the non-NC scheme. On the other hand, if we set $\mathcal{L}$ to include the set of outgoing NC links combinations only, the NC scenario as shown in Fig. 3b, which is conventional NC, is considered. In this way the LP with new $\mathcal{L}$ characterizes the throughput optimization problem of the conventional NC scheme. After solving the LPs for the non-NC scheme, conventional NC scheme, and analog NC scheme, respectively, we can obtain the network throughput of the non-NC, conventional NC, and analog NC schemes for wireless mesh networks.



■ **Figure 4.** *The network throughput gain of wireless NC schemes over the non-NC scheme in the random graph network with 34 nodes.*

Joint Link Scheduling, Channel Assignment, and Routing Algorithm

Routing Strategies

Our developed framework supports both multipath and single-path routing strategies. In other words, a given session can have either a single path or multiple paths. Intuitively, a multipath coding strategy can provide the most coding opportunity for the wireless NC schemes. However, for some routing schemes, multipath strategy is not applicable due to the high routing maintenance overhead. Thus, we also consider two types of single-path routing strategies: shortest single-path routing and optimized single-path routing. In particular, single-path routing can be obtained by Dijkstra's algorithm. On the other hand, the key idea of optimized single-path routing is to select the path that provides the maximum flow in the multipath routing for each session. Optimized single-path routing can be obtained by the following two steps. First, we solve the LP with multipath routing. For each session, we select the path that achieves the highest flow. Second, we input these obtained optimized single-path routes for each session to the LP and re-solve the LP.

Link Scheduling and Channel Assignment

Solving LP, we obtain the optimal flows for each link and NC links combination. We then develop the link scheduling and channel assignment algorithm based on the solution to the LP, which aims at approximately attaining the optimal flow derived by LP. Due to the node hardware constraints, the radio transceiver has to work over an assigned channel for a period of time before it can switch to another different channel. Let T_s ($T_s \geq 1$) be this period of time in the unit of time slots. Thus, we can update the channel assignment every T_s time slots.

Note that the problem of optimal channel assignments is NP-hard. We therefore design a heuristic greedy algorithm to obtain the schedule, which approximates the optimal solution derived by the LP. The solution to LP is the input of the link scheduling and channel assignment algorithm. The key idea of our link scheduling and channel assignment algorithm is to assign the flows to channels in as few time slots as possible. We implement this in a greedy way every T_s time slots. In every T_s time slots, we first deal with the NC flows. In particular, we sort the NC links combinations in decreasing order of the unassigned flows. The NC links combinations with larger unassigned flows have higher priority to select the channels. After we process all NC links combinations, we start the procedure of channel assignments and link schedule for the unicast traffic, which is very similar to that for NC traffic. After going through all the NC traffic and all the links for the unicast traffic, we check if there are still unassigned flows. If so, we move on to the next T_s time slots and repeat the scheduling process for both NC traffic and unicast traffic until all unassigned flows become zero. Note that the solution to LP contains the routing information for each session. The final outputs of the link scheduling and channel assignment algorithm arethe joint link scheduling, channel assignment, and routing approach, which approximately obtain the optimal throughput for each session under wireless mesh networks.

Performance Evaluation

In this section we validate and evaluate the performance of various wireless NC schemes over the non-NC scheme in multichannel multiradio wireless mesh networks where there are multiple unicast sessions. We focus on the random-graph topology network, where 34 nodes are arbitrarily deployed in a square region with each side being 3.3 units long. Specifically, the analog NC scheme with only three-node NC links combinations, referred to as NC3, is the NC scheme that takes advantage of NC links combinations in which at most three nodes are involved. The possible NC links combinations of the NC3 scheme are those shown in Figs. 3a and 3b. On the other hand, the fully functional analog NC scheme, referred to as NC5, is the NC scheme that utilizes all possible and realistic NC links combinations. The NC links combinations that are enabled by the NC5 scheme include those shown in Figs. 3a–3d. We set the communication range of each node and the interference range to be 1 unit and 1.4 units, respectively. We assume a free-space wireless channel model in which the link data rate depends only on the distance between two nodes of the link.

We solve the linear program using AMPL [10] with the `LP_SOLVE` solver to obtain the theoretically optimized network throughputs and the corresponding flows for the non-NC scheme, conventional NC scheme, NC3 scheme, and NC5 scheme, respectively. Then we calculate the network throughput gains of the three NC schemes over the non-NC scheme. Regarding the routing strategies, we consider shortest single-path routing, multipath routing, and optimized single-path routing. We also compare the theoretical network throughput (i.e., the solution of LP) with the experimental network throughput obtained by our designed joint link scheduling, channel assignment, and routing algorithm. The value of T_s in the algorithm is set to one time unit in the following evaluations.

We first study the network throughput gain of wireless NC schemes over the non-NC scheme. Each node has one radio, and there is only one channel in the networks. Figure 4 shows the network throughput gains of wireless NC schemes over the non-NC scheme. For any given wireless NC scheme, multipath routing can significantly increase the network throughput gain as compared to single-path routing. It is expected because the larger number of routes per session implies that there are more NC opportunities along the routes. It is interesting to note that when single-path routing is employed, the throughput gain of NC5 is exactly the same as that of NC3. This implies that NC5 does not have NC links combinations that contain more than 3 nodes, and thus NC5 degrades to NC3. From Fig. 4, the network throughput gain of the wireless scheme fluctuates as the number of sessions increases. This is because the number of NC links combinations is not persistent when the number of sessions changes. Overall, NC5 and NC3 can increase network throughput by 24 and 18 percent, respectively, on average over that with the conventional NC scheme.

Figure 5 shows the different performance impacts when the different routing strategies are used. Multipath routing can greatly benefit the network throughput for wireless NC schemes. The optimized single-path routing strategy achieves better network throughput than the shortest single-path routing strategy. The improvement of multipath routing over optimized single-path routing is noticeable in the random graph network. As shown in Fig. 5, we also compare the theoretical network throughput obtained by solving LP with the experimental network throughput achieved by implementing our developed joint link scheduling, channel assignment, and routing algorithm. There is a gap between the theoretical and experimental network throughput. It is more difficult for our heuristic algorithm to obtain the optimal channel assignments when the percentage of NC traffic is higher. The efficiency of our algorithm is about 0.77 on average when NC5 and multipath routing strategy are adopted. When single-path routing is used, the efficiency of our algorithm can reach up to 0.9. We also notice that given the same routing strategies, the efficiency of our algorithm is higher for the conventional NC scheme than for the NC5 scheme.

Finally, we study how multiradio and multichannel affect the performance of wireless NC schemes when multipath routing is adopted. The performance evaluations of multiradio and multichannel under single-path routing strategies is omitted here since they are similar to those under the multipath routing. Figure 6 shows the performance impact of multiradio and multichannel. The impacts of multiradio and multichannel on the wireless NC schemes and non-NC scheme are similar. The network throughput increases linearly with the number of channels when the number of radios is larger than the number of channels. This implies that at least (M – 1) radios per node are needed in order to make the best use of M channels. Given the same number of radios and number of channels, NC5 achieves the highest network throughput while the non-NC scheme achieves the lowest.

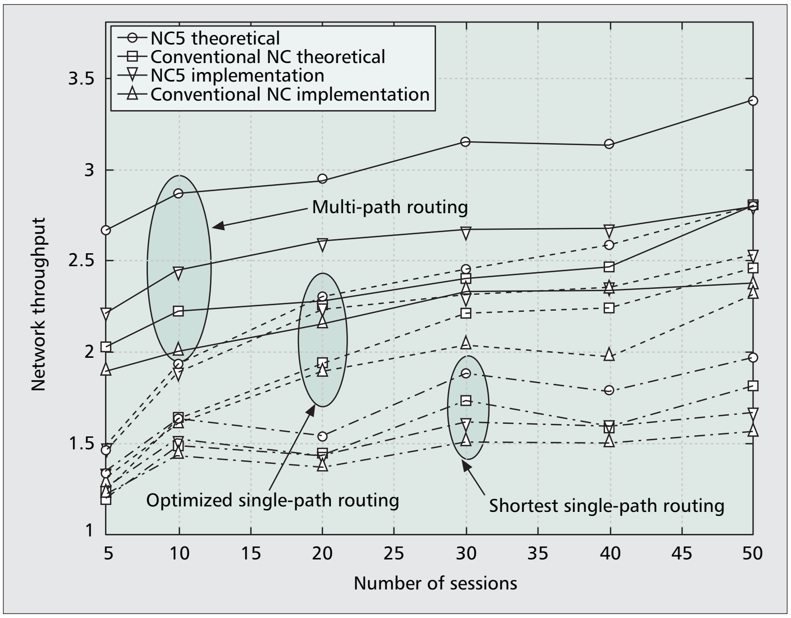


Figure 5. *The impact of routing strategies on network throughput. The solid lines, dotted lines, and dotted-dashed lines with different symbols represent the different schemes under multipath routing, optimized single-path routing, and shortest single-path routing, respectively.*

Conclusions

We modeled the throughput gains of both the conventional NC and analog NC schemes over the traditional non-NC scheme in multichannel multiradio wireless mesh networks. We formulated a general linear programming framework to solve the throughput optimization problems for the traditional non-NC scheme and the two types of wireless NC schemes. Under this framework, we quantitatively analyzed the network throughput gains of two types of wireless NC in different network topologies for wireless mesh networks with multiple unicast sessions. We also developed a joint link scheduling, channel assignment, and routing algorithm for the wireless NC schemes to closely approximate the optimal solutions. Our extensive simulations showed that the network throughput achieved by the analog NC scheme increases by 24 and 34 percent on average as compared to the conventional NC scheme and non-NC scheme, respectively.

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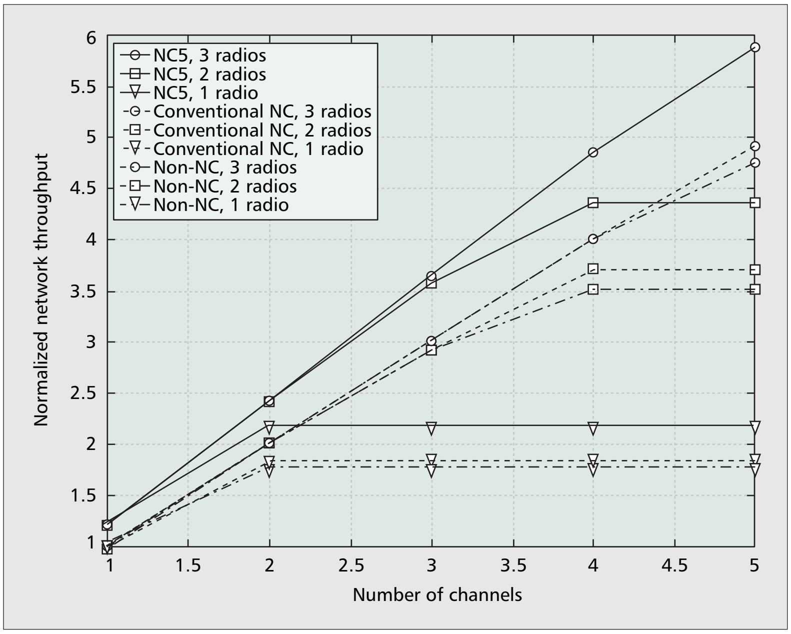

■ **Figure 6.** *The performance impact of multichannel and multiradio in the random graph network where there are 20 unicast sessions.*

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BIOGRAPHIES

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