OFDMA-Based Channel-Width Adaptation in Wireless Mesh Networks

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***Abstract*—Channel-width adaptation can optimize multiple performance metrics of a wireless communication link, including transmission rate, communication range, resilience to delay spread, and power consumption. Supporting variable channel width has been considered one of the most critical features of a communication radio. How to leverage a channel-width adaptive radio to improve throughput of a wireless network is a challenging problem in the medium access control (MAC) layer. So far, there exist research results on either theoretical analysis or protocol implementation for a point-to-multipoint (PMP) infrastructure network. However, the impact of channel width to a multihop wireless network has not been fully investigated yet. More specifically, how to exploit variable channel width to enhance throughput of a multihop wireless network remains an unresolved research issue. This paper addresses this issue in wireless mesh networks (WMNs) considering orthogonal frequency-division multiple-access (OFDMA)-based channel-width adaptation. Theoretical analysis is first carried out to identify appropriate algorithms for channel width adaptation. To this end, resource allocation with OFDMA-based channel-width adaptation is formulated as an optimization problem, which is proved to be NP-complete. To reduce the computational complexity, a greedy algorithm is derived to obtain a suboptimal solution. Based on such a greedy algorithm, a distributed MAC protocol is designed for channel-width adaptation for OFDMA-based WMNs. It takes advantage of variable channel width in different time slots to achieve highly efficient resource allocation. Simulation results illustrate that the distributed MAC protocol significantly outperforms MAC protocols based on traditional channel-width adaptation.**

***Index Terms*—Channel-width adaptation, distributed medium access control (MAC) protocol, wireless mesh networks (WMNs).**

I. Introduction

ADJUSTING channel width can optimize a few performance metrics of a wireless communication link. For example, given a certain level of transmission power, reducing the channel width of a wireless link can reliably increase its communication range; if the channel width is further reduced, then the power consumption can be also decreased without compromising the communication range. Thus, channel-width adaptation can optimize both communication range and power consumption that are usually in conflict with each other in a wireless link with fixed channel width [1]. Considering another scenario where a vehicular network is built based on orthogonal frequency-division multiplexing (OFDM), when a vehicle moves from a rural area to a suburb area, the delay spread of its communication link may increase to a level larger than the guard interval of OFDM symbols; however, reducing channel width is effective to fix this problem [2].

Because of the benefits of channel-width adaptation, supporting multiple options of channel width in a communication radio has become a common practice. For example, many IEEE 802.11 chipsets made by Atheros (now part of Qualcomm) support channel widths of 5, 10, 20, and 40 MHz. Similarly, WiMAX and long-term evolution chipsets also support a set of different channel widths. However, how to utilize such communication radios to improve network performance is a nontrivial task because a wireless network usually involves many communication links that all demand channel-width adaptation. In a point-to-multipoint (PMP) wireless network such as the IEEE 802.11 basic service set in infrastructure mode or an extended PMP network such as the IEEE 802.11 extended service set, research work has been conducted to utilize channel-width adaptation. In [1], the advantages of channel-width adaptation are analyzed using commodity IEEE 802.11 radios. A simple channel-width adaptation algorithm is derived for the basic scenario of a single link with two communication nodes. In [3] and [4], the channel widths of all access points in the distribution system of an IEEE 802.11 network are optimized according to different traffic load distributions in each basic service set. As a result, the throughput and the fairness of bandwidth distribution of the entire IEEE 802.11 network are greatly enhanced [3], [4]. A general case of adaptive channel-width allocation in base stations considering the demands of clients is analyzed in [5], where throughput maximization is formulated as a maximum bipartite flow problem.

The channel-adaptation algorithms in [1] and [3]–[5] are not applicable to a multihop wireless network because they all assume that the network works in a single-hop infrastructure mode. For multihop wireless networks, there still lack channel-width adaptation algorithms. Different types of multihop wireless networks are characterized by different features, which leads to different requirements and challenges in channel-width adaptation. For example, in a mobile ad hoc network, channel-width adaptation can be utilized to compensate delay spread and increase link stability. However, since the network

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IEEE Proof

topology is highly variable due to mobility, allocating different channel widths to different links is an extremely challenging task. In a wireless mesh network (WMN) [6], mobility is minimal. In particular, in the infrastructure of a WMN, all communication links remain stationary [6]. As a result, issues such as communication range, delay spread, and link stability can be considered during the network design and deployment phase. However, there exists one highly variable parameter that impacts the performance of WMNs, which is traffic load distribution on each link. It is rather common in WMNs that some links experience heavy traffic, whereas other links support only light traffic. To conduct efficient resource allocation for these links, a link with light traffic must be assigned with a very small resource unit, whereas a link with heavy traffic needs a large number of such resource units. If a time slot with fixed channel width is considered as a resource unit, then it is difficult to achieve the fine granularity of a small resource unit. For example, in many wireless networks, a link with fixed channel width can deliver a rate of 50 Mb/s or more; to achieve a resource unit of 100 Kb/s, the time slot length is 240 μs when the frame size is 1500 bytes and can be as small as 24 μs when the frame size is 150 bytes. Implementing such a small time slot is extremely challenging and can also result in large overhead due to the need of guard time. This problem can be properly solved by leveraging channel-width adaptation. More specifically, a fine-grained resource unit can be achieved by reducing channel width in a time slot. Thus, in this paper, channel-width adaptation algorithms and protocols are developed to satisfy heterogeneous traffic demands on various links in WMNs.

Traditionally, channel width of a link can be adjusted by selecting different options (e.g., 5, 10, 20, and 40 MHz) available in a radio. To consider finer channel-width adaptation, orthogonal frequency-division multiple-access (OFDMA) is adopted. We consider a single-radio WMN, where each radio adopts OFDMA. The channel width in a time slot of each radio is adjusted by selecting a different number of subchannels. Thus, the problem of channel-width adaptation to heterogeneous traffic demands in various links is converted to another problem, i.e., how to allocate subchannels and time slots to different links of a WMN such that the throughput of the entire network is maximized. We have made the following contributions in this paper.

1) Channel-width adaptation is proposed to resolve the issue of mismatch between link capacity and traffic demands. Instead of a traditional adaptation mechanism by choosing different available spectrum (i.e., frequency center and frequency bandwidth), OFDMA-based channel-width adaptation is proposed as a new mechanism. Based on this new mechanism, the channel-width adaptation problem in WMNs is converted into a time slot and subchannel allocation problem.
2) An optimization problem is formulated to investigate the channel-width adaptation problem in WMNs. The corresponding decision problem of this optimization problem is proved to be NP-complete, which reveals the complexity of channel-width adaptation in WMNs. To reduce the complexity, a greedy algorithm is proposed to obtain a suboptimal solution. With the feasible solution from the greedy algorithm as the initial population, a genetic algorithm (GA) is derived to obtain a near-optimal solution. Taking the GA as a reference, the greedy algorithm is shown to achieve comparable performance as that of a near-optimal solution.
3) It is shown that the greedy algorithm can be executed in a distributed way. Thus, this algorithm is incorporated into a distributed medium access control (MAC) protocol for channel-width adaptation in OFDMA WMNs. The MAC protocol is highly adaptive to dynamic network conditions such as variable traffic demands of wireless links. Thus, the throughput of the entire network is greatly improved.

The remainder of this paper is organized as follows. The basic mechanisms and benefits of channel-width adaptation based on OFDMA are explained in Section II, where related work is also presented. The time slot and subchannel allocation problem for channel-width adaptation is formulated in Section III, where a greedy algorithm and a GA are developed to obtain a near-optimal solution to resource allocation. Based on the greedy algorithm, a distributed MAC protocol is designed in Section IV. Performance results are presented in Section V, and the paper is concluded in Section VI.

II. Channel-Width Adaptation Based on Orthogonal Frequency-Division Multiple-Access: Mechanisms, Benefits, and Related Work

A. *OFDMA-Based Channel-Width Adaptation Mechanisms*

We consider a single-radio WMN. Traditionally, the channel width of a link can be adjusted by selecting: 1) different options of channel width (e.g., 5, 10, 20, and 40 MHz) available in a radio; and 2) the center frequency of the operation channel spectrum. However, the performance of this approach is impacted by several drawbacks. First, the granularity of channel-width adjustment is constrained, and thus, the step size of channel-width adjustment is limited. For example, the minimum channel width in an IEEE 802.11 radio must be 5 MHz and the step size is 5, 10, or 20 MHz. Second, the operation spectrum of a channel on a radio must be consecutive.

In this paper, a different approach is proposed to adjust channel width. It is based on the capability of subchannels (i.e., a number of subcarriers) allocation of OFDMA. Compared with a radio with traditional channel-width adaptation, an OFDMA-based radio brings several advantages.

1) It is flexible to adjust channel width to support traffic demand by selecting a different number of subchannels.
2) It does not require the spectrum of the selected subchannels to be consecutive, and the step size of channel-width adaptation can be as fine as one subchannel.
3) A single OFDMA radio node can support multiple communication links at the same time.

B. *Benefits of the OFDMA-Based Channel-Width Adaptation*

The benefits of the OFDMA-based channel-width adaptation are demonstrated in the following example.

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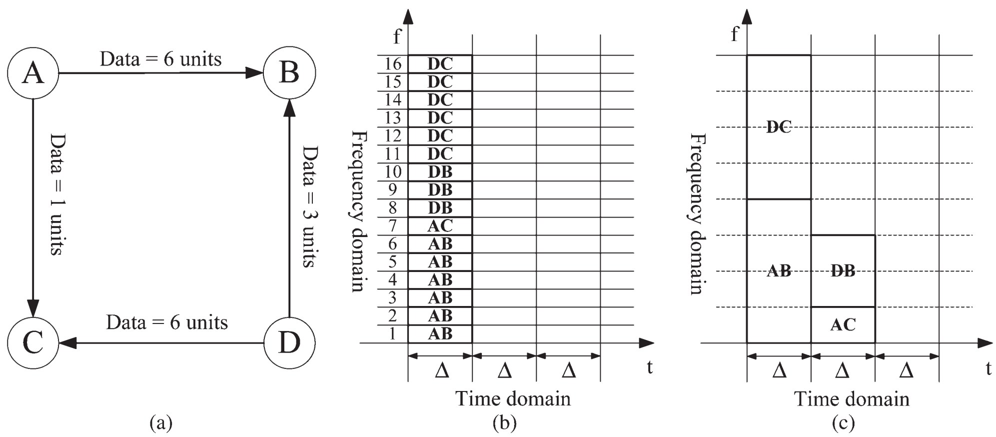

Fig. 1. Benefits of the OFDMA-based channel-width adaptation scheme. (a) Communication topology. (b) OFDMA-based scheme. (c) Traditional scheme.

A simple WMN with four nodes A, B, C, and D is considered in Fig. 1(a), where each node is equipped with one radio. The links are directional, and the whole spectrum is assumed to be 40 MHz. In the case of the OFDMA-based channel-width adaptation mechanism, the whole spectrum is divided into 16 subchannels. For the traditional channel-width adaptation scheme, channel width can only be selected from {5, 10, 20, 40} MHz, but the center frequency of a channel can be arbitrarily adjusted. We assume that subchannels are allocated to nodes slot by slot, and one subchannel per time slot Δ can convey 1 unit traffic demand. In Fig. 1(a), the traffic demands in links AB, AC, DB, and DC are 6, 1, 3, and 6 units, respectively.

Considering the OFDMA-based channel-width adaptation scheme, the subchannel and time slot allocation is shown in Fig. 1(b). To support all traffic demands, the time-division multiple-access (TDMA) frame can be as short as Δ, and the throughput of the network is $(6+1+3+6)/1 = 16$ (units/Δ).

Considering the traditional channel-width adaptation scheme, the channel and time slot allocation is shown in Fig. 1(c). To support all traffic demands, the TDMA frame needs to be 2Δ. Thus, the throughput of the network is $(6+1+3+6)/2 = 8$ (units/Δ).

This simple example demonstrates that the network throughput can be greatly improved by the OFDMA-based channel-width adaptation scheme for the following reasons: 1) An OFDMA radio can support several communication links simultaneously; and 2) the granularity of channel-width adjustment of an OFDMA radio can be as small as a subchannel.

However, two issues specific to OFDMA-based channel-width adaptation need to be considered: 1) channel-width adaptation in both frequency domain and time domain, i.e., both time slot and subchannel allocation; and 2) *transmitting* and *receiving constraint*, i.e., in a time slot, the subchannels allocated to a radio can only be used for either transmitting or receiving packets because full duplex wireless communications [7] are not considered in the OFDMA radio.

C. Related Work

So far many research papers have addressed the channel allocation problem in WMNs. For papers on single-radio multichannel operation [8]–[10], their results are not applicable to the OFDMA-based channel-width adaptation because fixed channel width is assumed. For papers on multiradio multichannel operation [11], [12], their algorithms cannot be adopted either because in the OFDMA-based channel-width adaptation, there exists a constraint that each node can either transmit or receive packets on subchannels at one time slot, whereas this constraint is not considered in the multiradio multichannel scenarios. In [13], a different channel width is available through channel combining on a radio for the WMNs. However, the approach explained in [13] is different from our OFDMA-based scheme in a single-radio WMN in two aspects: 1) In [13], one node can only maintain one communication link. However, in our scheme, one node can simultaneously support several communication links with different nodes; and 2) in [13], a radio can only use continuous channels, but a radio in our scheme can transmit on any subchannels in the communication band. To date, there also exist research results on subcarrier allocation for OFDMA WMNs. In [14], fair allocation of subcarrier and power is studied for a specific WMN with one mesh router and multiple mesh clients. Thus, their point-to-many-points (PMP) structure is different from our ad hoc network model. In [15], a joint power-subcarrier-time allocation algorithm is derived for one cluster of a WMN. In each cluster, the mesh router is responsible for resource assignment for its mesh clients. Thus, their network structure is also PMP. More recently, the resource-allocation problem of multihop OFDMA WMNs has been conducted in [16]–[19]. However, these papers focus on a relay-based two-hop network model. Thus, their algorithms are not applicable to a generic WMN. Consequently, to solve the subchannel allocation problem for channel-width adaptation in generic WMNs, new resource-allocation algorithms need to be derived and an appropriate one must be identified to conduct channel-width adaptation in a distributed MAC protocol, which is the focus of this paper.

III. Channel-Width Adaptation Algorithms Based on Orthogonal Frequency-Division Multiple-Access

Here, the resource-allocation problem considering channel-width adaptation is formulated first, and then the corresponding greedy and GAs are derived.

IEEE Proof

A. Problem Formulation

We consider a WMN consisting of N nodes and L directional links. Each node is equipped with an OFDMA radio. The transmission range of each node is R, and the interference range is R'. The network is modeled as a directional communication graph $G(V, A)$, where V is a set of nodes and A is a set of directed edges. Moreover, $|V| = N$ and $|A| = L$. Thus, for link $l(i, j) \in A$, node $i \in V$ is specified as the sending node and node $j \in V$ is the receiving node.

OFDMA is considered in the WMN; hence, a resource unit is a subchannel in a certain time slot. The length of a time slot is fixed, but the TDMA frame length is variable according to the fluctuating traffic demands of all links in the WMN. More specifically, when resource allocation is performed, the total number of time slots is determined such that traffic demands of all links are satisfied within a TDMA frame. This design eliminates the need of admission control, which is a preferred feature of data networks. To be consistent with this design, the traffic demand of a link is not specified as the actual traffic load. Instead, it is specified as the number of resource units per TDMA frame, and each unit represents the data transmitted in one subchannel per time slot, which is the same as the definition in Section II-A. For easy specification of traffic demands, when a node needs to specify the traffic demand of a link, it selects a traffic demand level from the set of $\{1, 2, \ldots, M\}$ (units), and the selected level is proportional to its expected actual traffic load. This design of the TDMA frame structure and the resource-allocation mechanism achieves time slotted resource sharing among links of all nodes, which is well suited for data networks.

In our OFDMA-based channel-width adaptation mechanism, it is assumed that the whole spectrum is divided into W subchannels and one subchannel supports one unit of traffic demand per time slot. The OFDMA-based radio can transmit data on any combination of these subchannels.

We use the protocol model [20] as the interference model. Under this model, a transmission from node i to node j in a time slot is successful if two conditions are satisfied: 1) $d_{ij} \leq R$, where d_{ij} is the distance between node i and node j; 2) any node k that occupies at least one overlapping subchannel with link $l(i, j)$ and $d_{kj} \leq R'$ is not transmitting. Moreover, a unit of traffic demand means the equivalent data rate that can be supported by a subchannel per time slot. Although the physical layer parameters (such as channel gain and rate adaptation) can impact the data rate of a subchannel per time slot, such impact can be captured by different units of traffic demand. In other words, given the same traffic load, the equivalent units of traffic demand are higher for a lower rate subchannel. Thus, physical layer parameters are not explicitly considered in the protocol model. Due to the OFDMA technique, the problem of channel-width adaptation can be converted into a resource-allocation problem: given traffic demands on different links, how time slots and subchannels are assigned under some constraints such that the total traffic demands are satisfied with the least number of time slots, i.e., the network throughput is maximized. This resource-allocation problem is formulated as follows. First, our objective is to minimize the number of time slots (i.e., the length of one TDMA frame) that can support the given traffic demands. Suppose that the total number of time slots consumed by the WMN is denoted as T, then the objective function becomes

$$Minimize\, T. \tag{1}$$

Obviously, T lies in the positive integer set, i.e.,

$$T \in \{1, 2, \ldots\}. \tag{2}$$

To help determine time slot and subchannel allocation for each directional link, $X(i, j, t, s)$ is used to denote the allocation status of link $l(i, j)$ in time slot t and subchannel s. Since $X(i, j, t, s) \in \{0, 1\}$, we have the following constraint:

$$\begin{aligned} &X(i, j, t, s) \in \{0, 1\} \\ &\forall l(i, j) \in A \quad \forall t = 1, 2, \ldots, T \quad \forall s = 1, 2, \ldots, W. \end{aligned} \tag{3}$$

To capture potential interference between links, we need a *link interference constraint* described as follows:

$$\begin{aligned} &X(i, j, t, s) + X(p, q, t, s) \leq 1 \\ &\forall l(i, j) \in A \qquad \forall t = 1, 2, \ldots, T \qquad \forall s = 1, 2, \ldots, W \\ &\forall l(p, q) \in I_{l(i,j)} \end{aligned} \tag{4}$$

where $I_{l(i,j)}$ is the interference set of link $l(i, j)$.

Since each mesh node has a single radio, it either transmits or receives on all the occupied subchannels in the same time slot. Thus, for a certain link $l(i, j)$, we have the following *transmitting* and *receiving constraint* (i.e., *Tx/Rx constraint*):

$$\begin{aligned} X(i, j, t, s) \times \Bigg[X(i, j, t, s) + \sum_{f=1}^{W} \sum_{p \in \mathrm{in}(i)} X(p, i, t, f) \\ + \sum_{g=1}^{W} \sum_{q \in \mathrm{out}(j)} X(j, q, t, g) \Bigg] \leq 1 \\ \forall l(i, j) \in A \qquad \forall t = 1, 2, \ldots, T \qquad \forall s = 1, 2, \ldots, W \end{aligned} \tag{5}$$

where $\mathrm{in}(i)$ is a set of nodes that send data to node i. Similarly, $\mathrm{out}(j)$ is the set of nodes that receive data from node j.

Finally, to satisfy the traffic demand of each link $l(i, j) \in A$, we need to consider the *traffic demand constraint*

$$\begin{aligned} &\sum_{t=1}^{T} \sum_{s=1}^{W} X(i, j, t, s) \geq D(i, j) \\ &D(i, j) \in \{1, 2, \ldots, M\} \end{aligned} \tag{6}$$

where $D(i, j)$ represents the units of traffic demand on link $l(i, j)$. This constraint means that each link must be assigned with enough time slots and subchannels to support its traffic demand.

Consequently, we have formulated the optimization problem of time slot and subchannel allocation for OFDMA-based channel-width adaptation. We call this problem the single-radio OFDMA-based resource-allocation (SRORA) problem. In summary, SRORA needs to optimize the objective in (1), subject to constraints in (2)–(6). In the following theorem, we prove that SRORA is NP-complete.

IEEE Proof

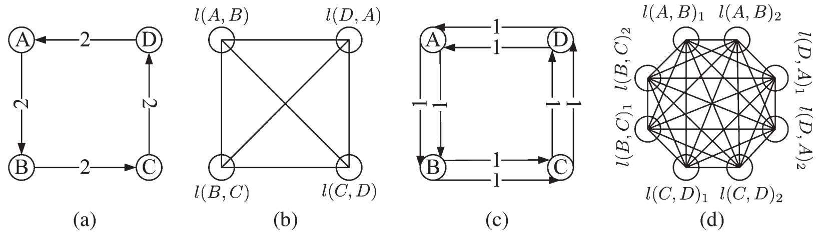

Fig. 2. (a) Communication graph $G(V, A)$, which consists of four directional communication links. Each link has 2 units of traffic demands. Based on the protocol interference model, $G(V, A)$ is converted into the interference graph G' in (b), where each vertex represents a directional communication link in $G(V, A)$. (c) Split communication graph of $G(V, A)$. It is constructed by splitting a communication link in $G(V, A)$ into several links, each with one unit of traffic demand, e.g., $l(A, B)$ in $G(V, A)$ has two units of traffic demands; hence, it is split into $l(A, B)_1$ and $l(A, B)_2$ in G_{split}, each with one unit of traffic demand. (d) Interference graph of the split communication graph G_{split}. (a) $G(V, A)$. (b) G'. (c) G_{split}. (d) G'_{split}.

Theorem 1: In SRORA, the decision problem of verifying whether K time slots are enough to satisfy the total traffic demands is NP-complete.

Proof: First, for any candidate solution of time slot and subchannel allocation, whether all the constraints are satisfied can be verified in polynomial time. Thus, the decision problem in SRORA is NP. Second, we consider the special case of SRORA by setting $W = 1$ and $D(i, j) = 1$ for all links. Using the protocol interference model, we convert the directional link $l(i, j) \in A$ in the communication graph $G(V, A)$ into the vertex in the corresponding interference graph G', as shown in Fig. 2. Based on the interference graph G', each link $l(i, j)$ in the communication graph $G(V, A)$ can construct an interference set $I_{l(i,j)}$. Since in this special case only one subchannel and one unit of traffic demand are considered for each link, only one time slot is needed in a frame to satisfy *traffic demand constraint* (6). To satisfy *link interference constraint* (4), any link in $I_{l(i,j)}$ must be assigned a different time slot from that of link $l(i, j)$. In this special case, when *link interference constraint* (4) is satisfied, Tx/Rx *constraint* (5) is also automatically satisfied due to the two facts: 1) The links $l(p, i)$ where $p \in \text{in}(i)$ and links $l(j, q)$ where $q \in \text{out}(j)$ are in set $I_{l(i,j)}$; and 2) the link in $I_{l(i,j)}$ is assigned with a different time slot from the link $l(i, j)$. Therefore, the problem of determining whether K time slots are enough to support the traffic demands of all links in the communication graph $G(V, A)$ is equivalent to the problem of checking whether K colors are sufficient to color the vertices in the corresponding interference graph G'. We know that the latter problem is NP-complete [21], which means that every problem in NP is reducible to the decision problem of SRORA in polynomial time. As a result, the decision problem of SRORA (in the special case) is NP-complete. In the general case (with W subchannels and $D(i, j)$ traffic demand), the decision problem is also NP-complete. □

B. Greedy Algorithm

Since the problem SRORA is NP-complete, a low-complexity greedy algorithm is proposed for the SRORA problem, and we call it GR-SRORA. In our greedy algorithm, links are assigned with time slot and subchannel in a certain sequential order just like coloring the vertices in the corresponding interference graph. However, here we also need to consider Tx/Rx *constraint.*

GR-SRORA is described in Algorithm 1. It works as follows.

1) Lines 2–15 specify the procedures of assigning the time slot and subchannel to link $l(i, j)$ considering both *link interference constraint* and Tx/Rx *constraint*. The resource-allocation status table of link $l(i, j)$, denoted by $\Phi(i, j, t, s)$, captures *link interference constraint*. More specifically, for any t and s, if $\Phi(i, j, t, s) = 1$, it means that subchannel s in time slot t is occupied by a link in the interference set of link $l(i, j)$ (i.e., $I_{l(i,j)}$). The single-radio OFDMA constraint table of link $l(i, j)$, denoted by $\Psi(i, j, t)$, captures Tx/Rx *constraint*. More specifically, for any t, if $\Psi(i, j, t) = 1$, it means that link $l(i, j)$ cannot transmit on any subchannel in time slot t.
2) Lines 16–19 are executed after a link assignment. Two tables ($\Phi(p, q, t, s)$ and $\Psi(p, q, t)$) of each link are updated and will be used in the next link assignment.
3) Line 21 is used to determine T_{greedy}, which is the total number of time slots consumed by the network following the greedy algorithm.

The performance of the greedy algorithm GR-SRORA is analyzed as follows. We denote the minimum number of time slots consumed in SRORA and the greedy algorithm GR-SRORA as T_{optimal} and T_{greedy}, respectively. Based on the split graph G_{split} of the original communication graph $G(V, A)$ and the split interference graph G'_{split} in Fig. 2, the relationship between T_{optimal} and T_{greedy} is shown in Theorem 2.

Algorithm 1 GR-SRORA

Input:
- Communication graph $G(V, A)$
- Resource consumption status table of link $l(i, j)$: $\Phi(i, j, t, s)$
- Single-radio OFDMA constraint table of link $l(i, j)$: $\Psi(i, j, t)$
- Traffic demand on link $l(i, j)$: $D(i, j)$
- Number of total subchannels: W

Output:
- Network time slot consumption: T_{greedy}
- The maximum time slot assigned to link $l(i, j)$: $T_{l(i,j)}$
- Time slot and subchannel allocation result for link $l(i, j)$: $X(i, j, t, s)$

IEEE Proof

Initialization:

- $\Phi(i,j,t,s) = 0$
- $\Psi(i,j,t) = 0$
- $T_{\text{greedy}} = 0$
- $T_{l(i,j)} = 0$

```
1: for all l(i,j) ∈ A do
2:  for t = 1 to +∞ do
3:   if D(i,j) == 0 then
4:    Break;
5:   end if
6:   if Ψ(i,j,t)! = 1 then
7:    for s = 1 to W do
8:     if D(i,j) > 0 && Φ(i,j,t,s) == 0 then
9:      X(i,j,t,s) = 1
10:     D(i,j) = D(i,j) − 1
11:     T_l(i,j) = t
12:    end if
13:   end for
14:  end if
15: end for
16: for all l(p,q) ∈ A do
17:  Update Φ(p,q,t,s)
18:  Update Ψ(p,q,t)
19: end for
20: end for
21: T_greedy = max_{l(i,j)∈A} T_l(i,j)
22: Stop.
```

Theorem 2: For the optimal solution of the problem SRORA T_{optimal} and the greedy solution of GR-SRORA T_{greedy}, $\lceil(\chi(G'_{\text{split}})/W)\rceil \le T_{\text{optimal}} \le T_{\text{greedy}} \le T_{\max} = \delta(G'_{\text{split}})+1$, where $\lceil\cdot\rceil$ is the ceiling function, $\delta(\cdot)$ is the maximum degree of a graph, and $\chi(\cdot)$ is the chromatic number of a graph. Moreover, G'_{split} is the interference graph constructed by splitting a AQ2 communication link in $G(V,A)$ into separate links, each with one unit traffic demand.

Proof: The proof consists of two parts. First, we derive the lower bound of T_{optimal} by looking into the property of T_{optimal}. In the communication graph $G(V,A)$, each directional link $l(i,j)$ (with traffic demand $D(i,j)$) is split into $D(i,j)$ virtual directional links between node i and node j to construct the split communication graph G_{split}, as shown in Fig. 2(c). Based on the protocol interference model, the split communication graph G_{split} is converted into its corresponding interference graph G'_{split}, as shown in Fig. 2(d). If each vertex of G'_{split} is greedily colored, i.e., assigning different time slot–subchannel pairs to interfering virtual links G_{split}, then each link in communication graph $G(V,A)$ certainly satisfies the *link interference constraint*. The minimum number of colors (i.e., time slot–subchannel pairs) that G'_{split} consumes is the chromatic number $\chi(G'_{\text{split}})$ [22]. Since W subchannels are available for each time slot, the minimum number of consumed time slots becomes $\lceil(\chi(G'_{\text{split}})/W)\rceil$, when only *link interference constraint* is taken into account. However, in SRORA, there exists the Tx/Rx *constraint*; hence, the optimal number of time slots (i.e., T_{optimal}) must be larger than or equal to $\lceil(\chi(G'_{\text{split}})/W)\rceil$. In other words, $\lceil(\chi(G'_{\text{split}})/W)\rceil \le T_{\text{optimal}}$ holds.

Second, we derive the upper bound of T_{optimal} by exploring the property of T_{greedy}. We consider the worst case where there exists only one subchannel (i.e., $W = 1$). Given any link assignment order $\vec{\mathcal{L}}$ taken by GR-SRORA, there exists a corresponding greedy coloring order in G'_{split}. For any greedy coloring order in G'_{split}, the number of colors that are needed is at most $\delta(G'_{\text{split}})+1$ [23]. Since the number of colors in G'_{split} is exactly equal to the number of time slots needed in the worst case communication graph, i.e., $T^{\text{worst}}_{\text{greedy}}(\vec{\mathcal{L}})$, thus, for any link AQ3 assignment order $\vec{\mathcal{L}}$, the number of time slots that are consumed is upper bounded by $T_{\max} = \delta(G'_{\text{split}})+1$. In general, the number of subchannels W is usually a constant greater than 1. Thus, for any link assignment order $\vec{\mathcal{L}}$, the total number of time slots needed by GR-SRORA $T_{\text{greedy}}(\vec{\mathcal{L}})$ is equal or smaller than $T^{\text{worst}}_{\text{greedy}}(\vec{\mathcal{L}})$. Thus, $T_{\text{greedy}} \le T_{\max} = \delta(G'_{\text{split}})+1$.

Combining the lower bound and the upper bound, we have $\lceil(\chi(G'_{\text{split}})/W)\rceil \le T_{\text{optimal}} \le T_{\text{greedy}} \le T_{\max} = \delta(G'_{\text{split}})+1$, which proves Theorem 2. □

The complexity of the GR-SRORA is analyzed as follows. In GR-SRORA, the number of links L is a variable, but subchannel number W and traffic demand upper bound M for each link are constants. In Algorithm 1, lines 2–15 are for assigning time slots and subchannels to link $l(i,j)$. Its complexity is $\mathcal{O}(T_{\max})$, where $T_{\max}$ is the upper bound of T_{greedy}. As shown in Theorem 2, $T_{\max} = \delta(G'_{\text{split}})+1$. Since $\delta(G'_{\text{split}})+1 \le M \times L + 1$, hence, $T_{\max} \le M \times L + 1$. Thus, the complexity from lines 2–15 is $\mathcal{O}(L)$. Lines 16–19 are to update $\Phi(i,j,t,s)$ and $\Psi(i,j,t)$. The complexity is $\mathcal{O}(L)$. Thus, considering lines 1–22, the complexity is $L \times (\mathcal{O}(L) + \mathcal{O}(L))$. Therefore, the total complexity is $\mathcal{O}(L^2)$.

C. GA

Since the greedy algorithm, i.e., GR-SRORA, usually can only obtain the suboptimal solution, we adopt a GA to obtain a near-optimal result as a theoretical reference for our greedy algorithm.

To apply the GA, the number of decision variables $X(i,j,t,s)$ in the optimization problem SRORA needs to be constant. Since for a certain network the number of links L and the number of subchannels W are constants, we also need to fix the total time slots for assignment so that the number of $X(i,j,t,s)$ will be fixed. From the proof of Theorem 2, T_{optimal} is upper bounded by $T_{\max} = \delta(G'_{\text{split}})+1$ for a given communication graph $G(V,A)$. With this bound, the problem SRORA is reformulated as follows:

$$Minimize\ T.$$

$$\text{s.t.}\begin{cases} X(i,j,t,s) + X(p,q,t,s) \le 1 \\ \Big[X(i,j,t,s) + \sum_{f=1}^{W}\sum_{p\in\text{in}(i)} X(p,i,t,f) \\ \quad + \sum_{g=1}^{W}\sum_{q\in\text{out}(j)} X(j,q,t,g)\Big] \times X(i,j,t,s) \le 1 \\ \sum_{t=1}^{T_{\max}}\sum_{s=1}^{W} X(i,j,t,s) \ge D(i,j) \\ X(i,j,t,s) \in \{0,1\} \\ \forall l(i,j) \in A \qquad \forall s = 1,2,\ldots,W \\ \forall l(p,q) \in I_{l(i,j)} \qquad \forall t = 1,2,\ldots,T_{\max}. \end{cases}$$

IEEE Proof

The objective T is the maximum occupied time slot in the network and is calculated with decision variable $X(i,j,t,s)$ as $T = \max_{t\in\{1,2,\ldots,T_{\max}\}} t$, subject to $\max_{l(i,j)\in A, s\in\{1,2,\ldots,W\}} X(i,j,t,s) \neq 0$. The previous optimization problem is exactly the same as SRORA, except that the range of t is upper bounded by $T_{\max}$ instead of T. Thus, its complexity is the same as SRORA, i.e., it is also NP-complete.

Based on this new formulation, a GA is developed for SRORA. We call it GA-SRORA. Different from classic optimization methods such as gradient-based approaches, GA is well suited for integer programming problems. Although there is no absolute guarantee for the GA-SRORA to obtain an optimal solution, the algorithm can be executed for sufficient time to reach a near-optimal solution.

GA evolves its generation into the next generation via three essential steps: reproduction, crossover, and mutation. Thus, GA-SRORA is executed according to the following steps.

1) Initialize Population: The population of our algorithm GA-SRORA consists of chromosomes. Each chromosome is represented by $X(i,j,t,s)$ of all links.
2) Evaluation and Fitness Assignment: For every chromosome, its fitness needs to be minimized in GA-SRORA. The fitness captures the objective function and the constraints in the reformulated SRORA problem. As a result, the fitness is described as

$$
\begin{aligned}
&\mathit{Fitness} \\
&\quad = T + P \times (C_1 + C_2 + C_3) \\
&C_1 = \sum_{l(i,j)\in A} \max\left[0, 1 - \sum_{t=1}^{T_{\max}} \sum_{s=1}^{W} X(i,j,t,s)/D(i,j)\right] \\
&C_2 = \sum_{l(i,j)\in A} \sum_{l(p,q)\in I_{l(i,j)}} \sum_{t=1}^{T_{\max}} \sum_{s=1}^{W} \max \\
&\qquad \times [0, X(i,j,t,s) + X(p,q,t,s) - 1] \\
&C_3 = \sum_{l(i,j)\in A} \sum_{t=1}^{T_{\max}} \sum_{s=1}^{W} \max \\
&\qquad \times \left[0, \left(X(i,j,t,s) + \sum_{f=1}^{W} \sum_{p\in \mathrm{in}(i)} X(p,i,t,f)\right.\right. \\
&\qquad\quad \left.\left. + \sum_{g=1}^{W} \sum_{q\in \mathrm{out}(j)} X(j,q,t,g)\right) X(i,j,t,s) - 1\right]
\end{aligned}
$$

where T is the maximum occupied time slot in the network and is obtained with $X(i,j,t,s)$, P as a penalty parameter. C_1, C_2, and C_3 are derived from *traffic demand constraint*, *link interference constraint*, and Tx/Rx *constraint*, respectively.
3) Reproduction: According to the fitness, better chromosomes are copied and worse chromosomes are removed, whereas holding population size constant. A fair selection is applied to generate "winners" and put them into the "mating pool."
4) Crossover: Parent chromosomes swap a subset of their strings, generating two new chromosomes called children.
5) Mutation: A new chromosome is generated by changing value of one bit in its string. This step reduces the chance of falling into the local optimal point.
6) Steps 2–5 are repeated for U rounds to obtain a relatively stable solution.

The complexity of the GA-SRORA can be derived similarly to Algorithm 1. For iteration rounds U, population size V, and link number L, the complexity of GA-SRORA is $\mathcal{O}(UVL^3)$.

IV. Distributed Medium Access Control for Orthogonal Frequency-Division Multiple-Access-Based Channel-Width Adaptation

Here, a distributed MAC protocol is designed based on the greedy algorithm for OFDMA-based channel-width adaptation.

A. *Distributed Operation of the Greedy Algorithm*

Four information tables are maintained by every node i: 1) $Q_{\mathrm{in}}(i,p,q)$, which indicates whether subchannel q in time slot p is occupied by a receiving link (i.e., incoming link) of a node in the interference range of node i; 2) $Q_{\mathrm{out}}(i,p,q)$, which indicates whether subchannel q in time slot p is occupied by a sending link (i.e., outgoing link) of a node in the interference range of node i; 3) $O_{\mathrm{in}}(i,t)$, which indicates whether time slot t is occupied by any receiving link of node i; and 4) $O_{\mathrm{out}}(i,t)$, which indicates whether time slot t is occupied by any sending link of node i. How such information is collected is explained in Section IV-C and D.

For a given link $l(i,j)$, sending node i is responsible for assigning time slots and subchannels to support a given number of units (denoted as $D(i,j)$) in a TDMA frame. With these variables, resource allocation of link $l(i,j)$ is executed as follows.

1) Information fusion: Based on the protocol interference model, any receiving link of a node located in the interference range of node i or any sending link of a node located in the interference range of node j potentially interferes with link $l(i,j)$; hence, node i needs to communicate with node j to collect all the resource-allocation information by combining tables $Q_{\mathrm{in}}(i,p,q)$ and $Q_{\mathrm{out}}(j,p,q)$ before resource allocation is conducted. Due to the single-radio OFDMA Tx/Rx *constraint*, node i also needs to obtain table $O_{\mathrm{out}}(j,t)$ from node j, and then determines which time slot is still available by checking $O_{\mathrm{in}}(i,t)$ and $O_{\mathrm{out}}(j,t)$.
2) Time slot and subchannel allocation: For the first time slot, node i assigns the unoccupied subchannels to link $l(i,j)$ to support the traffic demands. If the first time slot is not enough, it goes to the second time slot. This process is repeated until the sum of the assigned subchannels can support the traffic demand of link $l(i,j)$. During this period, any link $l(p,q) \in I_{l(i,j)}$ (i.e., $l(p,q)$ is any receiving link of a node located in the interference range of node i or any sending link of a node located in the interference range of node j) cannot conduct resource allocation simultaneously.

IEEE Proof

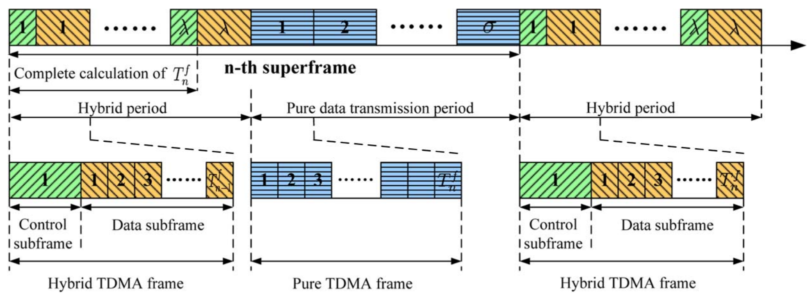

Fig. 3. Frame structure.

3) Information table update: After resource allocation of link $l(i,j)$, all nodes in the interference range of node i and node j update their information tables immediately.

To support the aforementioned mechanisms, the control messages need to be received within the interference range. To this end, the lowest transmission rate is adopted by control messages.

Since every node contends to assign resources to its outgoing links in a greedy way, two nodes that are far away enough can conduct resource allocation simultaneously. As a result, resource allocation in the entire WMN is conducted in a distributed way and is thus called distributed GR-SRORA (DGR-SRORA). Based on this distributed resource-allocation process, a distributed multisubchannel TDMA MAC protocol is developed in the following sections.

B. Frame Structure

The new MAC protocol works in a hybrid way, as shown in Fig. 3. In each superframe, a new resource allocation is carried out in λ control subframes, and data transmissions proceed on the assigned time slots and subchannels.

A superframe includes two parts, namely, hybrid period and pure data transmission period. The hybrid period consists of λ hybrid TDMA frames, where λ is a constant and must be set large enough for all the nodes to complete resource allocation. A hybrid TDMA frame is composed of two subframes: control subframe and data subframe. Each consists of a number of time slots. The control subframe is used for resource allocation. The data subframe is used for data transmission. The pure data transmission period consists of σ pure TDMA frames, where σ is a constant. These TDMA frames are only used for data transmission.

As shown in Fig. 3, in the nth superframe, the length of the data subframe in the hybrid period is T_{n-1}^f, which is determined in the $(n-1)$-th superframe. In the hybrid period of the nth superframe, our resource-allocation algorithm determines a new length of a TDMA frame T_n^f. This new value updates the length of a pure TDMA frame in the pure data transmission period of the nth superframe. It also determines the length of the data subframe in the hybrid period of the $(n+1)$-th superframe. As a result, in Fig. 3, the frame lengths in the left hybrid TDMA frame and the right hybrid TDMA frame are equal to T_{n-1}^f and T_n^f, respectively.

In the control subframe of the hybrid period, each node uses an request-to-send/clear-to-send mechanism to contend for time slots' and subchannels' allocation. In all TDMA frames for data transmission, each node adopts carrier-sense multiple access/collision avoidance to access the assigned time slots and subchannels. This can prevent collisions due to allocation error or out-of-network interference. As a result, our MAC protocol is actually a *TDMA MAC overlaying CSMA/CA*.

C. Distributed Resource-Allocation Procedure

The control subframe in Fig. 3 is used to signal distributed resource allocation. Control messages are sent with the lowest transmission rate using all subchannels. For resource assignment of link $l(i,j)$, the negotiation between node i and node j follows this procedure.

1) Node i sends a request-to-assign (RTA) packet to node j. All nodes except node j in the sensing range of node i keep quiet.
2) Upon receiving the RTA packet, node j sends node i a clear-to-assign (CTA) packet, which contains $Q_{\text{out}}(j,p,q)$ and $O_{\text{out}}(j,t)$. All nodes except node i in the sensing range of node j keep quiet.
3) Upon receiving the CTA packet, node i relies on tables $Q_{\text{in}}(i,p,q)$, $Q_{\text{out}}(j,p,q)$, $O_{\text{in}}(i,t)$, and $O_{\text{out}}(j,t)$ to assign time slots and subchannels to link $l(i,j)$. Then, node i broadcasts an announcement (ANN) packet, which contains the assignment result for link $l(i,j)$, to all nodes in its interference range.
4) Upon receiving the ANN packet, all nodes in the interference range of node i update their tables. Node j also broadcasts an ANN packet to all nodes in its interference range, and then such receiving nodes update their information tables.

An example of resource-allocation procedure is explained next. The signaling messages are transmitted in the lowest rate to cover all the nodes in the interference range, and the exchange procedure is shown in Fig. 4.

1) Node A starts to assign time slots and subchannels for link $l(A,B)$. It broadcasts an RTA packet to node B. Node C and node D can receive the signaling packet; hence, they keep quiet.
2) Node B receives the RTA packet and then broadcasts a CTA packet, which contains $Q_{\text{out}}(B,p,q)$ and $O_{\text{out}}(B,t)$, to node A. Nodes A and C can receive this packet, but node D can only sense it.
3) Node A receives the CTA packet and broadcasts an ANN packet, which contains the assignment result for link $l(A,B)$. Node B receives this packet, but nodes C and D can only sense it.

IEEE Proof

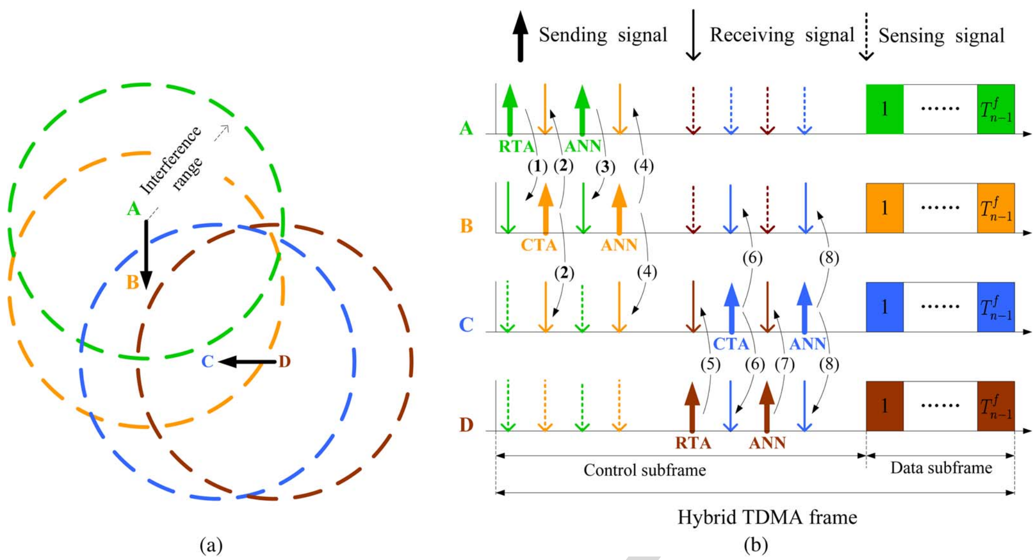

Fig. 4. Operation of the MAC protocol: An example. (a) Topology. (b) Resource negotiation.

4) When node B receives the ANN packet, it updates its own information tables and rebroadcasts the ANN packet. Nodes A and C receive it and update their tables, but node D can only sense it.
5) Node D starts to assign time slots and subchannels for link $l(D, C)$. It broadcasts an RTA packet to node C. Node A and node B can sense the signaling; hence, they keep quiet.
6) Node C receives the RTA packet and then broadcasts a CTA packet, which contains $Q_{\text{out}}(C, p, q)$ and $O_{\text{out}}(C, t)$, to node D. Node D and node B can receive this packet, but node A can only sense it.
7) Node D receives the CTA packet and broadcasts an ANN packet, which contains the allocation result of link $l(D, C)$. Node C receives this packet, but node A and node B can only sense it.
8) When node C receives the ANN packet, it updates its own information tables and rebroadcasts the ANN packet. Nodes D and B receive it and update their information tables, but node A can only sense it.

In the distributed algorithm, every node determines its own time slot. Thus, the largest time slot in one node may be different from that of another node. To avoid inconsistent TDMA frame in different links, the largest time slot in the allocation must be known to all nodes. This can be done by the following simple procedure. When a node gets resource-allocation information from another node, it compares its largest time slot with that in the allocation information. If its own value is smaller, it needs to update its largest time slot number and broadcast the updated information to its neighbors; otherwise, no action is needed.

D. Enhancement for Multiple Interference Domains

The aforementioned protocol is effective for the single interference domain because every time only one link is in the resource-allocation process and other nodes can hear signaling messages and keep quiet. However, in the case of multiple interference domains, there exist collisions in ANN packets. For example, in Fig. 5, node B and node F successfully make reservation for link $l(B, A)$ and link $l(F, G)$ by exchanging RTA and CTA packets. However, it is possible that the ANN packets broadcast by node B and node F simultaneously and interfere each other at node D. Thus, node D cannot receive the ANN packet, which leads to errors in the following resource assignment in other links. To reduce the probability of collisions in ANN packets, we propose a scheme as follows. During the resource-allocation process of link $l(i, j)$, node i and node j exchange RTA and CTA packets as usual. The process of broadcasting ANN packets is modified to reduce the collision probability: 1) Node i and node j broadcast ANN packets in turn for K_{ANN} rounds instead of only one round; and 2) before broadcasting an ANN packet, the sending node randomly chooses a waiting time in the backoff window W_{ANN} and delays the ANN packet transmission for the chosen waiting time.

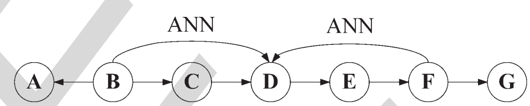

Fig. 5. ANN packet collision may occur in the case of multiple interference domains.

Although this scheme cannot guarantee collision-free ANN packets, the collision probability dramatically drops with the increased K_{ANN} and W_{ANN}. It should be noted that how to design an effective distributed MAC protocol in multiple interference domains still remains a challenging problem.

V. Performance Results

Here, MATLAB simulations are carried out to evaluate our algorithms and protocols developed in previous sections. Since the objective of our algorithms and protocols is to leverage channel-width adaptation to efficiently support diverse traffic demands in different links of a WMN, transmission rate in different links is assumed to be homogeneous. Performance results from such a setting provide a better demonstration about

IEEE Proof

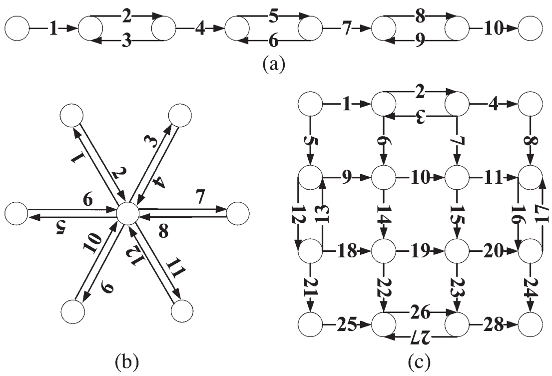

Fig. 6. Simple topologies.

how channel-width adaptation improves throughput; the impact from heterogeneous link rates is eliminated. In simulations, the homogeneous link rate is equal to 54 Mb/s when the bandwidth is 20 MHz. The total available bandwidth is 40 MHz; hence, the corresponding link rate using a whole spectrum is 108 Mb/s. Moreover, a single radio is considered in each mesh node.

In our OFDMA-based channel-width adaptation scheme, the whole spectrum is divided into 64 subchannels and the length of a time slot is 5 ms. We assume that one subchannel per time slot can transmit 1 unit of traffic demand. If a link is assigned two subchannels every three time slots, then its throughput is $(2/3) \times (108/64) = 1.125$ Mb/s. The network throughput is defined as the ratio of the total supported traffic demands over the length of a TDMA frame.

To fully evaluate our algorithm and protocols, different network topologies are considered in the following sections. The details of network setup and the corresponding traffic demands are specified separately for each topology.

A. Simple Topologies

The greedy algorithm and GA are evaluated under three simple topologies in Fig. 6. In each topology, the link ID is marked in the figure, and all the links have the same length, which represents the communication range. The interference range is set twice the communication range.

For each link, the traffic demand is uniformly distributed in $\{1, \ldots, 128\}$ (units).

For each topology, we evaluate the network throughput that can be achieved in a WMN with available bandwidth of 40 MHz. The performance results of our channel-width adaptation algorithms (i.e., GR-SRORA and GA-SRORA) are compared with that achieved by the single-radio traditional channel-width adaptation (SRTCWA) scheme and also with that achieved by the single-radio fixed channel-width (SRFCW) scheme. SRTCWA and SRFCW are executed following the same procedure as GR-SRORA (i.e., greedily assign time slot and channel to all the links in the same order as GR-SRORA) but consider different constraints. In SRTCWA, there are four options of channel width (i.e., 5, 10, 20, and 40 MHz), and the center frequency of each channel can be adjusted. In SRFCW, the radio on each node uses a 20-MHz channel. To be fair in comparison, two orthogonal channels (i.e., totally 40 MHz) are available in SRFCW for parallel links in the same interference domain.

In the string topology, as shown in Fig. 7(a), on average, the network throughput of GR-SRORA is 19.2% higher than that achieved by SRTCWA and 30.8% higher than that of SRFCW. In this network structure, the throughput improvement is not significant due to lack of PMP structure in the string topology.

In the star topology, as shown in Fig. 7(b), on average, the network throughput of GR-SRORA is 54.5% higher than that of SRTCWA and 136.4% higher than that of SRFCW. The improvement is significant because our OFDMA-based channel-width adaptation scheme is very suitable for exploring channel-width adaptive concurrent transmissions in a star network structure.

In the grid topology, as shown in Fig. 7(c), on average, the network throughput of GR-SRORA is 19.3% higher than that of SRTCWA and 29.8% higher than that of SRFCW.

As shown in Fig. 7, the greedy algorithm achieves nearly the same throughput as that of the GA-based algorithm, which indicates that the greedy algorithm is effective to obtain a near-optimal solution to the channel-width adaptation problem in WMNs.

B. Randomized Topology

Our distributed MAC protocol is also evaluated in a randomized topology. The communication range of each node is 100 m, the interference range is 200 m, and the sensing range is 300 m. The RTA and CTA packets have a length of 120 bytes, and the ANN packet has a length of 30 bytes. As explained in Section IV, the lowest transmission rate is adopted to send these packets, and it is set to 6 Mb/s.

1) Single Interference Domain Scenario: In this scenario, nodes are randomly distributed within a circle with a diameter of 200 m. Since all nodes can hear each other, no collision is associated with ANN packets. The distributed MAC protocol (DGR-SRORA) in Section IV is adopted. The ANN packets are broadcast only for one round. In the simulation, six cases of node–link pairs are considered: 10 nodes 15 links, 10 nodes 20 links, 20 nodes 30 links, 20 nodes 40 links, 30 nodes 45 links, and 30 nodes 60 links. For each case, the nodes are randomly distributed and the links are randomly selected. The traffic demand for each link is uniformly distributed within $\{1, \ldots, 128\}$ (units).

a) Network throughput: In each case of node–link pair, the distributed protocol DGR-SRORA is compared with SRTCWA and SRFCW. The network throughput of each case is averaged over five tests and is shown in Fig. 8. In all cases, our OFDMA-based channel-width adaptation scheme outperforms SRTCWA and SRFCW. Moreover, compared with the SRTCWA, DGR-SRORA improves the network throughput by 14.3%, 20.0%, 18.5%, 15.0%, 13.3%, and 16.1%, respectively, in six cases. As compared with SRFCW, DGR-SRORA enhances the network throughput by 28.6%, 30.0%, 29.6%, 25.0%, 22.2%, and 24.2%, respectively, in six cases.

b) Resource-allocation delay: The total time required for the distributed resource-allocation procedure is investigated. In our simulation, the sum of the control subframe and the data

IEEE Proof

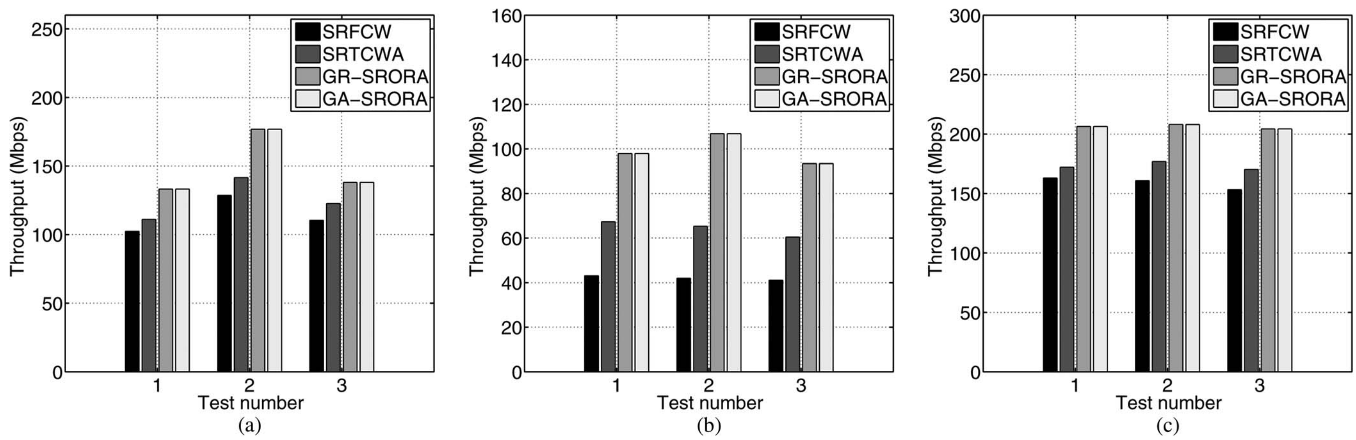

Fig. 7. Network throughput for simple topologies. (a) String topology. (b) Star topology. (c) Grid topology.

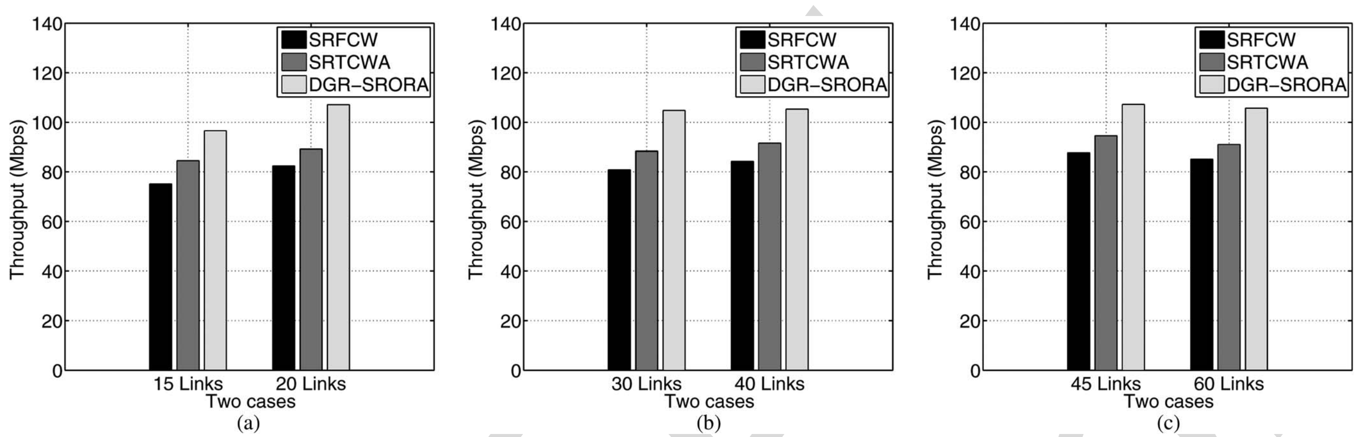

Fig. 8. Network throughput in the scenario of single interference domain. (a) 10 nodes. (b) 20 nodes. (c) 30 nodes.

TABLE I
TOTAL RESOURCE ALLOCATION TIME FOR THE SINGLE INTERFERENCE DOMAIN SCENARIO

Control Subframe	Data Subframe	Nodes: 10 Links: 15	Nodes: 10 Links: 20	Nodes: 20 Links: 30	Nodes: 20 Links: 40	Nodes: 30 Links: 45	Nodes: 30 Links: 60
20 ms	80 ms	9.2 ms	11.3 ms	18.4 ms	104.5 ms	112.1 ms	202.3 ms
15 ms	85 ms	9.2 ms	11.3 ms	103.9 ms	110.5 ms	202.4 ms	214.7 ms
10 ms	90 ms	9.2 ms	101.8 ms	200.5 ms	205.9 ms	305.7 ms	407.0 ms
5 ms	95 ms	104.0 ms	202.5 ms	304.7 ms	504.4 ms	801.5 ms	1100.5 ms

subframe (i.e., the length of a hybrid TDMA frame) is assumed to be 100 ms. For each case of node–link pair, we consider different lengths of control subframe and data subframe. The results are shown in Table I. For each case of node–link pair, when the control subframe is longer, the allocation delay is smaller. Thus, if we need a faster allocation procedure, a larger control subframe is necessary, which leads to more overhead in signaling. However, even if the overhead is less than 10% for signaling, the allocation can be done within 1 s for node–link pairs: 10–15, 10–20, 20–30, 20–40, and 30–45. Such a fast allocation procedure means that our MAC protocol is highly adaptive to dynamic network conditions such as topology change or traffic variations.

Scenario of Multiple Interference Domains: In this scenario, 50 nodes are randomly distributed in a square whose side length is 1000 m, as shown in Fig. 9. The distributed MAC protocol with modified ANN packet transmission in Section IV

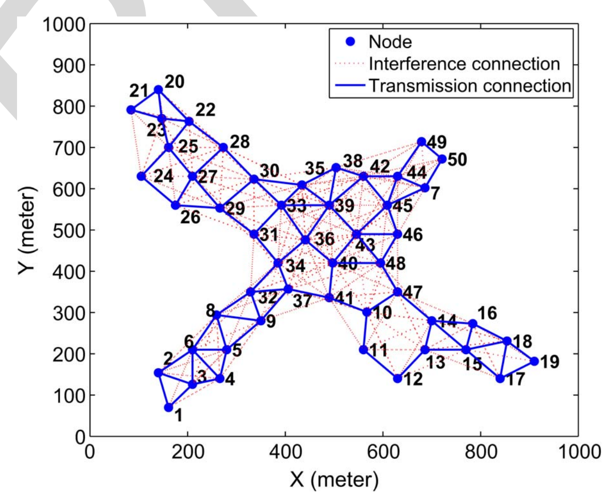

Fig. 9. Topology.

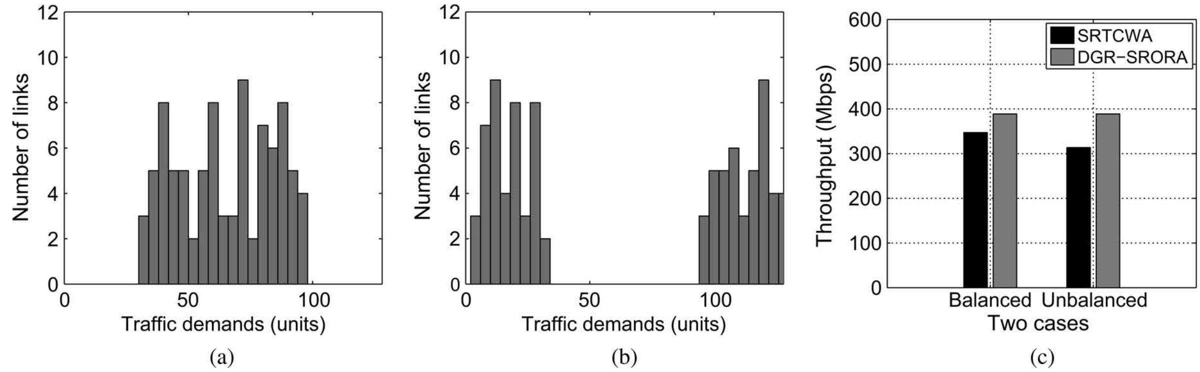

Fig. 10. Network throughput under different traffic distributions. (a) Balanced traffic distribution. (b) Unbalanced traffic distribution. (c) Network throughput.

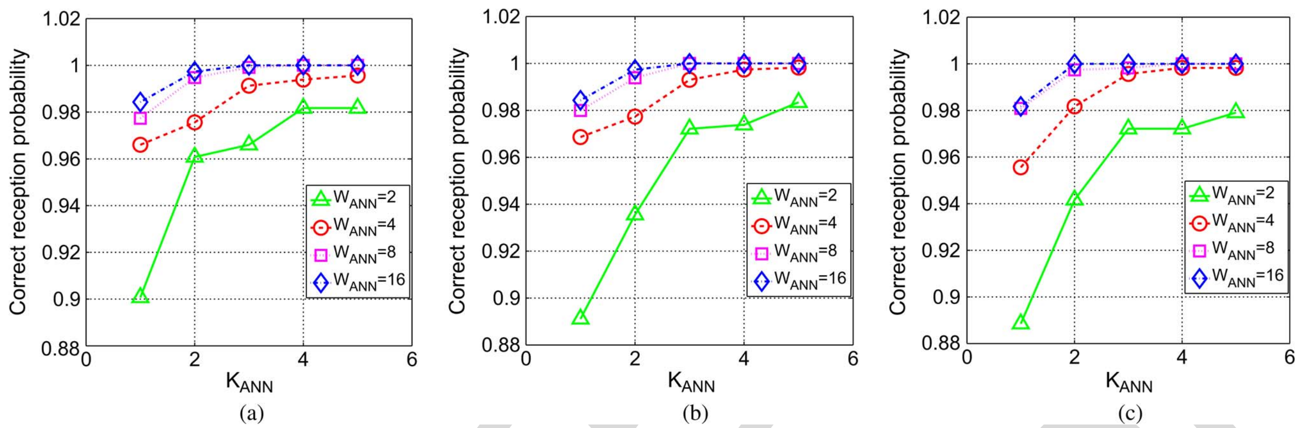

Fig. 11. ANN packet reception probability in the network with multiple interference domains. (a) Control subframe: 10 ms. (b) Control subframe: 15 ms. (c) Control subframe: 20 ms.

is adopted. In this protocol, the ANN packets are broadcast after a randomly chosen waiting time for several rounds.

c) Network throughput: The impact of the traffic distribution to the network throughput is illustrated in Fig. 9. Since there exists multiple interference domains, the distributed protocol DGR-SROTSA may have allocation error due to collision in ANN packets. Thus, we properly choose broadcasting rounds and backoff window to reduce collisions. We randomly choose 88 links in Fig. 9 for the test. Two cases with different traffic distributions are considered. In the first case, the traffic demand of each link is balanced and is uniformly distributed in $\{32, \ldots, 96\}$, as shown in Fig. 10(a). In the second case, the traffic demand of each link is unbalanced and is uniformly distributed in either $\{1, 32\}$ or $\{96, 128\}$, as shown in Fig. 10(b). The network throughputs of these two cases are shown in Fig. 10(c). As compared with the traditional channel-width adaptation scheme (i.e., SRTCWA), our MAC protocol with OFDMA-based channel-width adaptation improves the network throughput by 12% and 24%, respectively, in these two cases. Higher throughput improvement is achieved in the case of unbalanced traffic distribution because our MAC protocol leverages OFDMA-based channel-width adaptation to allocate resource in more proper way.

d) Performance of the modified ANN packet broadcasting mechanism: In Section IV-D, we propose that an ANN packet is broadcast after a randomly selected waiting time for several rounds to reduce the collision probability. In this experiment, this mechanism is investigated with respect to different broadcasting rounds K_{ANN} and backoff window W_{ANN}. In Fig. 9, we randomly choose 88 links for testing. Three cases (with 10-, 15-, and 20-ms control subframes) are considered. In each case, the number of broadcasting rounds K_{ANN} varies from 1 to 5, and the broadcasting delay is randomly chosen in the backoff window W_{ANN}. W_{ANN} is set 2, 4, 8, and 16 (the unit is the transmission time of an ANN packet), respectively. The reception probability of ANN packets is defined as the ratio of the correctly received ANN packets over total transmitted ANN packets. In Fig. 11, for the fixed K_{ANN} in all cases, the correct reception probability is higher with larger W_{ANN}. Similarly, for the fixed W_{ANN}, the correct reception probability increases with a larger K_{ANN}. In each case, when $K_{\mathrm{ANN}} = 3$ and $W_{\mathrm{ANN}} = 16$ or when $K_{\mathrm{ANN}} = 4$ and $W_{\mathrm{ANN}} = 8$, the reception probability near reaches 1.

e) Resource-allocation delay: The total delay required for the distributed resource-allocation procedure is also investigated. In our simulation, the sum of the control subframe and the data subframe is assumed to be 100 ms, and three cases (with 10-, 15-, and 20-ms control subframes) are considered. The results are shown in Table II. When the control subframe is longer, the allocation delay is smaller. Thus, if we need a faster

TABLE II
TOTAL RESOURCE ALLOCATION DELAY FOR THE SCENARIO OF MULTIPLE INTERFERENCE DOMAINS

Rounds	$W_{ANN}(10ms)^a$				$W_{ANN}(15ms)^b$				$W_{ANN}(20ms)^c$			
	2	4	8	16	2	4	8	16	2	4	8	16
K_{ANN}=1	$0.20s$	$0.31s$	$0.50s$	$1.01s$	$0.11s$	$0.20s$	$0.31s$	$0.51s$	$0.10s$	$0.11s$	$0.21s$	$0.41s$
K_{ANN}=2	$0.21s$	$0.40s$	$0.71s$	$1.21s$	$0.20s$	$0.21s$	$0.41s$	$0.81s$	$0.11s$	$0.20s$	$0.31s$	$0.52s$
K_{ANN}=3	$0.31s$	$0.50s$	$0.91s$	$1.70s$	$0.20s$	$0.30s$	$0.51s$	$1.11s$	$0.12s$	$0.21s$	$0.40s$	$0.71s$
K_{ANN}=4	$0.40s$	$0.60s$	$1.21s$	$2.70s$	$0.21s$	$0.40s$	$0.61s$	$1.51s$	$0.20s$	$0.30s$	$0.51s$	$0.90s$
K_{ANN}=5	$0.50s$	$0.70s$	$1.31s$	$3.30s$	$0.30s$	$0.41s$	$0.80s$	$1.70s$	$0.21s$	$0.31s$	$0.52s$	$1.10s$

[a]The length of the control subframe is 10 ms
[b]The length of the control subframe is 15 ms
[c]The length of the control subframe is 20 ms

allocation procedure, a larger control subframe is necessary, which leads to more overhead in signaling. In each case, for a fixed K_{ANN}, the allocation delay becomes larger as W_{ANN} increases. Similarly, for a fixed W_{ANN}, the allocation delay grows as K_{ANN} increases. For $K_{\text{ANN}} = 3$ and $W_{\text{ANN}} = 16$, the maximum resource-allocation delay among three cases is 1.70 s (i.e., in the 10 ms control subframe case). For $K_{\text{ANN}} = 4$ and $W_{\text{ANN}} = 8$, the maximum resource-allocation delay among three cases is 1.21 s (i.e., in the 10 ms control subframe case). Therefore, with 10% signaling overhead (due to the control subframe), the reception probability reaches 1 with a resource-allocation delay of less than 2 s.

VI. CONCLUSION

In WMNs, there always exists a mismatch between link capacity and traffic demand. In this paper, an OFDMA-based channel-width adaptation mechanism has been designed to alleviate such a mismatch of each link in WMNs. It was formulated as a time slot and subchannel allocation problem and was proved to be NP-complete. Thus, a greedy algorithm and a GA were derived to obtain a suboptimal solution. Based on the greedy algorithm, a distributed MAC protocol was developed to conduct channel-width adaptation for all links in the WMN. Simulation results showed that the new MAC protocol outperformed MAC protocols with traditional channel-width adaptation. The channel-width adaptation mechanism studied in this paper assumes that the traffic demand on each link is given. In practice, traffic demand of a link is closely related to MAC/routing cross-layer design. How to consider channel-width adaptation under the framework of MAC/routing cross-layer design is a key factor to further improve the network performance of WMNs, which is an interesting topic for future research.

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AQ1 = Please check if change made in this sentence is appropriate.
AQ2 = Semi-colon was changed to comma. Please check if appropriate.
AQ3 = The preceding statement is incomplete. Hence, it was combined with the subsequent sentence. Please check if appropriate.

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OFDMA-Based Channel-Width Adaptation in Wireless Mesh Networks

Xudong Wang, *Senior Member, IEEE*, Pengfei Huang, Jiang Xie, *Senior Member, IEEE*, and Mian Li

***Abstract*—Channel-width adaptation can optimize multiple performance metrics of a wireless communication link, including transmission rate, communication range, resilience to delay spread, and power consumption. Supporting variable channel width has been considered one of the most critical features of a communication radio. How to leverage a channel-width adaptive radio to improve throughput of a wireless network is a challenging problem in the medium access control (MAC) layer. So far, there exist research results on either theoretical analysis or protocol implementation for a point-to-multipoint (PMP) infrastructure network. However, the impact of channel width to a multihop wireless network has not been fully investigated yet. More specifically, how to exploit variable channel width to enhance throughput of a multihop wireless network remains an unresolved research issue. This paper addresses this issue in wireless mesh networks (WMNs) considering orthogonal frequency-division multiple-access (OFDMA)-based channel-width adaptation. Theoretical analysis is first carried out to identify appropriate algorithms for channel width adaptation. To this end, resource allocation with OFDMA-based channel-width adaptation is formulated as an optimization problem, which is proved to be NP-complete. To reduce the computational complexity, a greedy algorithm is derived to obtain a suboptimal solution. Based on such a greedy algorithm, a distributed MAC protocol is designed for channel-width adaptation for OFDMA-based WMNs. It takes advantage of variable channel width in different time slots to achieve highly efficient resource allocation. Simulation results illustrate that the distributed MAC protocol significantly outperforms MAC protocols based on traditional channel-width adaptation.**

***Index Terms*—Channel-width adaptation, distributed medium access control (MAC) protocol, wireless mesh networks (WMNs).**

I. Introduction

ADJUSTING channel width can optimize a few performance metrics of a wireless communication link. For example, given a certain level of transmission power, reducing the channel width of a wireless link can reliably increase its communication range; if the channel width is further reduced, then the power consumption can be also decreased without compromising the communication range. Thus, channel-width adaptation can optimize both communication range and power consumption that are usually in conflict with each other in a wireless link with fixed channel width [1]. Considering another scenario where a vehicular network is built based on orthogonal frequency-division multiplexing (OFDM), when a vehicle moves from a rural area to a suburb area, the delay spread of its communication link may increase to a level larger than the guard interval of OFDM symbols; however, reducing channel width is effective to fix this problem [2].

Because of the benefits of channel-width adaptation, supporting multiple options of channel width in a communication radio has become a common practice. For example, many IEEE 802.11 chipsets made by Atheros (now part of Qualcomm) support channel widths of 5, 10, 20, and 40 MHz. Similarly, WiMAX and long-term evolution chipsets also support a set of different channel widths. However, how to utilize such communication radios to improve network performance is a nontrivial task because a wireless network usually involves many communication links that all demand channel-width adaptation. In a point-to-multipoint (PMP) wireless network such as the IEEE 802.11 basic service set in infrastructure mode or an extended PMP network such as the IEEE 802.11 extended service set, research work has been conducted to utilize channel-width adaptation. In [1], the advantages of channel-width adaptation are analyzed using commodity IEEE 802.11 radios. A simple channel-width adaptation algorithm is derived for the basic scenario of a single link with two communication nodes. In [3] and [4], the channel widths of all access points in the distribution system of an IEEE 802.11 network are optimized according to different traffic load distributions in each basic service set. As a result, the throughput and the fairness of bandwidth distribution of the entire IEEE 802.11 network are greatly enhanced [3], [4]. A general case of adaptive channel-width allocation in base stations considering the demands of clients is analyzed in [5], where throughput maximization is formulated as a maximum bipartite flow problem.

The channel-adaptation algorithms in [1] and [3]–[5] are not applicable to a multihop wireless network because they all assume that the network works in a single-hop infrastructure mode. For multihop wireless networks, there still lack channel-width adaptation algorithms. Different types of multihop wireless networks are characterized by different features, which leads to different requirements and challenges in channel-width adaptation. For example, in a mobile ad hoc network, channel-width adaptation can be utilized to compensate delay spread and increase link stability. However, since the network

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topology is highly variable due to mobility, allocating different channel widths to different links is an extremely challenging task. In a wireless mesh network (WMN) [6], mobility is minimal. In particular, in the infrastructure of a WMN, all communication links remain stationary [6]. As a result, issues such as communication range, delay spread, and link stability can be considered during the network design and deployment phase. However, there exists one highly variable parameter that impacts the performance of WMNs, which is traffic load distribution on each link. It is rather common in WMNs that some links experience heavy traffic, whereas other links support only light traffic. To conduct efficient resource allocation for these links, a link with light traffic must be assigned with a very small resource unit, whereas a link with heavy traffic needs a large number of such resource units. If a time slot with fixed channel width is considered as a resource unit, then it is difficult to achieve the fine granularity of a small resource unit. For example, in many wireless networks, a link with fixed channel width can deliver a rate of 50 Mb/s or more; to achieve a resource unit of 100 Kb/s, the time slot length is 240 μs when the frame size is 1500 bytes and can be as small as 24 μs when the frame size is 150 bytes. Implementing such a small time slot is extremely challenging and can also result in large overhead due to the need of guard time. This problem can be properly solved by leveraging channel-width adaptation. More specifically, a fine-grained resource unit can be achieved by reducing channel width in a time slot. Thus, in this paper, channel-width adaptation algorithms and protocols are developed to satisfy heterogeneous traffic demands on various links in WMNs.

Traditionally, channel width of a link can be adjusted by selecting different options (e.g., 5, 10, 20, and 40 MHz) available in a radio. To consider finer channel-width adaptation, orthogonal frequency-division multiple-access (OFDMA) is adopted. We consider a single-radio WMN, where each radio adopts OFDMA. The channel width in a time slot of each radio is adjusted by selecting a different number of subchannels. Thus, the problem of channel-width adaptation to heterogeneous traffic demands in various links is converted to another problem, i.e., how to allocate subchannels and time slots to different links of a WMN such that the throughput of the entire network is maximized. We have made the following contributions in this paper.

1) Channel-width adaptation is proposed to resolve the issue of mismatch between link capacity and traffic demands. Instead of a traditional adaptation mechanism by choosing different available spectrum (i.e., frequency center and frequency bandwidth), OFDMA-based channel-width adaptation is proposed as a new mechanism. Based on this new mechanism, the channel-width adaptation problem in WMNs is converted into a time slot and subchannel allocation problem.
2) An optimization problem is formulated to investigate the channel-width adaptation problem in WMNs. The corresponding decision problem of this optimization problem is proved to be NP-complete, which reveals the complexity of channel-width adaptation in WMNs. To reduce the complexity, a greedy algorithm is proposed to obtain a suboptimal solution. With the feasible solution from the greedy algorithm as the initial population, a genetic algorithm (GA) is derived to obtain a near-optimal solution. Taking the GA as a reference, the greedy algorithm is shown to achieve comparable performance as that of a near-optimal solution.
3) It is shown that the greedy algorithm can be executed in a distributed way. Thus, this algorithm is incorporated into a distributed medium access control (MAC) protocol for channel-width adaptation in OFDMA WMNs. The MAC protocol is highly adaptive to dynamic network conditions such as variable traffic demands of wireless links. Thus, the throughput of the entire network is greatly improved.

The remainder of this paper is organized as follows. The basic mechanisms and benefits of channel-width adaptation based on OFDMA are explained in Section II, where related work is also presented. The time slot and subchannel allocation problem for channel-width adaptation is formulated in Section III, where a greedy algorithm and a GA are developed to obtain a near-optimal solution to resource allocation. Based on the greedy algorithm, a distributed MAC protocol is designed in Section IV. Performance results are presented in Section V, and the paper is concluded in Section VI.

II. Channel-Width Adaptation Based on Orthogonal Frequency-Division Multiple-Access: Mechanisms, Benefits, and Related Work

A. OFDMA-Based Channel-Width Adaptation Mechanisms

We consider a single-radio WMN. Traditionally, the channel width of a link can be adjusted by selecting: 1) different options of channel width (e.g., 5, 10, 20, and 40 MHz) available in a radio; and 2) the center frequency of the operation channel spectrum. However, the performance of this approach is impacted by several drawbacks. First, the granularity of channel-width adjustment is constrained, and thus, the step size of channel-width adjustment is limited. For example, the minimum channel width in an IEEE 802.11 radio must be 5 MHz and the step size is 5, 10, or 20 MHz. Second, the operation spectrum of a channel on a radio must be consecutive.

In this paper, a different approach is proposed to adjust channel width. It is based on the capability of subchannels (i.e., a number of subcarriers) allocation of OFDMA. Compared with a radio with traditional channel-width adaptation, an OFDMA-based radio brings several advantages.

1) It is flexible to adjust channel width to support traffic demand by selecting a different number of subchannels.
2) It does not require the spectrum of the selected subchannels to be consecutive, and the step size of channel-width adaptation can be as fine as one subchannel.
3) A single OFDMA radio node can support multiple communication links at the same time.

B. Benefits of the OFDMA-Based Channel-Width Adaptation

The benefits of the OFDMA-based channel-width adaptation are demonstrated in the following example.

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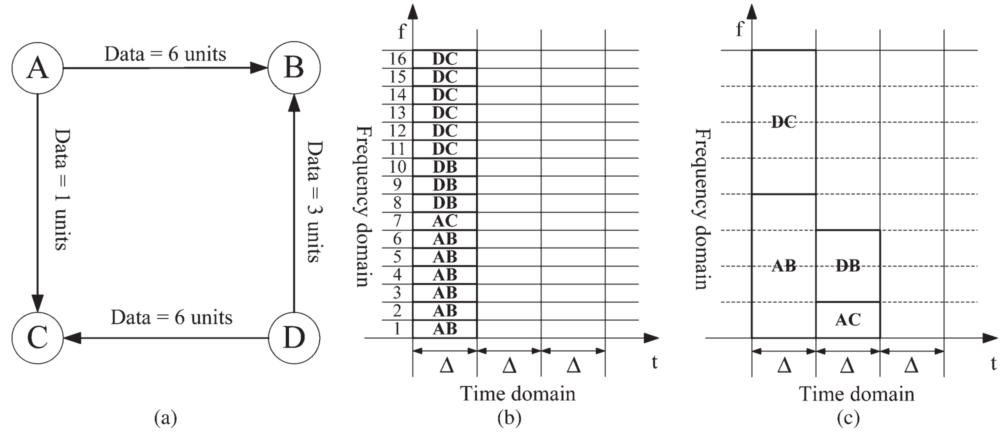

Fig. 1. Benefits of the OFDMA-based channel-width adaptation scheme. (a) Communication topology. (b) OFDMA-based scheme. (c) Traditional scheme.

A simple WMN with four nodes A, B, C, and D is considered in Fig. 1(a), where each node is equipped with one radio. The links are directional, and the whole spectrum is assumed to be 40 MHz. In the case of the OFDMA-based channel-width adaptation mechanism, the whole spectrum is divided into 16 subchannels. For the traditional channel-width adaptation scheme, channel width can only be selected from {5, 10, 20, 40} MHz, but the center frequency of a channel can be arbitrarily adjusted. We assume that subchannels are allocated to nodes slot by slot, and one subchannel per time slot Δ can convey 1 unit traffic demand. In Fig. 1(a), the traffic demands in links AB, AC, DB, and DC are 6, 1, 3, and 6 units, respectively.

Considering the OFDMA-based channel-width adaptation scheme, the subchannel and time slot allocation is shown in Fig. 1(b). To support all traffic demands, the time-division multiple-access (TDMA) frame can be as short as Δ, and the throughput of the network is $(6+1+3+6)/1 = 16$ (units/Δ).

Considering the traditional channel-width adaptation scheme, the channel and time slot allocation is shown in Fig. 1(c). To support all traffic demands, the TDMA frame needs to be 2Δ. Thus, the throughput of the network is $(6+1+3+6)/2 = 8$ (units/Δ).

This simple example demonstrates that the network throughput can be greatly improved by the OFDMA-based channel-width adaptation scheme for the following reasons: 1) An OFDMA radio can support several communication links simultaneously; and 2) the granularity of channel-width adjustment of an OFDMA radio can be as small as a subchannel.

However, two issues specific to OFDMA-based channel-width adaptation need to be considered: 1) channel-width adaptation in both frequency domain and time domain, i.e., both time slot and subchannel allocation; and 2) *transmitting* and *receiving constraint*, i.e., in a time slot, the subchannels allocated to a radio can only be used for either transmitting or receiving packets because full duplex wireless communications [7] are not considered in the OFDMA radio.

C. Related Work

So far many research papers have addressed the channel allocation problem in WMNs. For papers on single-radio multichannel operation [8]–[10], their results are not applicable to the OFDMA-based channel-width adaptation because fixed channel width is assumed. For papers on multiradio multichannel operation [11], [12], their algorithms cannot be adopted either because in the OFDMA-based channel-width adaptation, there exists a constraint that each node can either transmit or receive packets on subchannels at one time slot, whereas this constraint is not considered in the multiradio multichannel scenarios. In [13], a different channel width is available through channel combining on a radio for the WMNs. However, the approach explained in [13] is different from our OFDMA-based scheme in a single-radio WMN in two aspects: 1) In [13], one node can only maintain one communication link. However, in our scheme, one node can simultaneously support several communication links with different nodes; and 2) in [13], a radio can only use continuous channels, but a radio in our scheme can transmit on any subchannels in the communication band. To date, there also exist research results on subcarrier allocation for OFDMA WMNs. In [14], fair allocation of subcarrier and power is studied for a specific WMN with one mesh router and multiple mesh clients. Thus, their point-to-many-points (PMP) structure is different from our ad hoc network model. In [15], a joint power-subcarrier-time allocation algorithm is derived for one cluster of a WMN. In each cluster, the mesh router is responsible for resource assignment for its mesh clients. Thus, their network structure is also PMP. More recently, the resource-allocation problem of multihop OFDMA WMNs has been conducted in [16]–[19]. However, these papers focus on a relay-based two-hop network model. Thus, their algorithms are not applicable to a generic WMN. Consequently, to solve the subchannel allocation problem for channel-width adaptation in generic WMNs, new resource-allocation algorithms need to be derived and an appropriate one must be identified to conduct channel-width adaptation in a distributed MAC protocol, which is the focus of this paper.

III. Channel-Width Adaptation Algorithms Based on Orthogonal Frequency-Division Multiple-Access

Here, the resource-allocation problem considering channel-width adaptation is formulated first, and then the corresponding greedy and GAs are derived.

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A. Problem Formulation

We consider a WMN consisting of N nodes and L directional links. Each node is equipped with an OFDMA radio. The transmission range of each node is R, and the interference range is R'. The network is modeled as a directional communication graph $G(V, A)$, where V is a set of nodes and A is a set of directed edges. Moreover, $|V| = N$ and $|A| = L$. Thus, for link $l(i,j) \in A$, node $i \in V$ is specified as the sending node and node $j \in V$ is the receiving node.

OFDMA is considered in the WMN; hence, a resource unit is a subchannel in a certain time slot. The length of a time slot is fixed, but the TDMA frame length is variable according to the fluctuating traffic demands of all links in the WMN. More specifically, when resource allocation is performed, the total number of time slots is determined such that traffic demands of all links are satisfied within a TDMA frame. This design eliminates the need of admission control, which is a preferred feature of data networks. To be consistent with this design, the traffic demand of a link is not specified as the actual traffic load. Instead, it is specified as the number of resource units per TDMA frame, and each unit represents the data transmitted in one subchannel per time slot, which is the same as the definition in Section II-A. For easy specification of traffic demands, when a node needs to specify the traffic demand of a link, it selects a traffic demand level from the set of $\{1, 2, \ldots, M\}$ (units), and the selected level is proportional to its expected actual traffic load. This design of the TDMA frame structure and the resource-allocation mechanism achieves time slotted resource sharing among links of all nodes, which is well suited for data networks.

In our OFDMA-based channel-width adaptation mechanism, it is assumed that the whole spectrum is divided into W subchannels and one subchannel supports one unit of traffic demand per time slot. The OFDMA-based radio can transmit data on any combination of these subchannels.

We use the protocol model [20] as the interference model. Under this model, a transmission from node i to node j in a time slot is successful if two conditions are satisfied: 1) $d_{ij} \leq R$, where d_{ij} is the distance between node i and node j; 2) any node k that occupies at least one overlapping subchannel with link $l(i,j)$ and $d_{kj} \leq R'$ is not transmitting. Moreover, a unit of traffic demand means the equivalent data rate that can be supported by a subchannel per time slot. Although the physical layer parameters (such as channel gain and rate adaptation) can impact the data rate of a subchannel per time slot, such impact can be captured by different units of traffic demand. In other words, given the same traffic load, the equivalent units of traffic demand are higher for a lower rate subchannel. Thus, physical layer parameters are not explicitly considered in the protocol model. Due to the OFDMA technique, the problem of channel-width adaptation can be converted into a resource-allocation problem: given traffic demands on different links, how time slots and subchannels are assigned under some constraints such that the total traffic demands are satisfied with the least number of time slots, i.e., the network throughput is maximized. This resource-allocation problem is formulated as follows. First, our objective is to minimize the number of time slots (i.e., the length of one TDMA frame) that can support the given traffic demands. Suppose that the total number of time slots consumed by the WMN is denoted as T, then the objective function becomes

$$Minimize\, T. \tag{1}$$

Obviously, T lies in the positive integer set, i.e.,

$$T \in \{1, 2, \ldots\}. \tag{2}$$

To help determine time slot and subchannel allocation for each directional link, $X(i,j,t,s)$ is used to denote the allocation status of link $l(i,j)$ in time slot t and subchannel s. Since $X(i,j,t,s) \in \{0,1\}$, we have the following constraint:

$$\begin{aligned} & X(i,j,t,s) \in \{0,1\} \\ & \forall l(i,j) \in A \quad \forall t = 1, 2, \ldots, T \quad \forall s = 1, 2, \ldots, W. \end{aligned} \tag{3}$$

To capture potential interference between links, we need a *link interference constraint* described as follows:

$$\begin{aligned} & X(i,j,t,s) + X(p,q,t,s) \leq 1 \\ & \forall l(i,j) \in A \qquad \forall t = 1, 2, \ldots, T \qquad \forall s = 1, 2, \ldots, W \\ & \forall l(p,q) \in I_{l(i,j)} \end{aligned} \tag{4}$$

where $I_{l(i,j)}$ is the interference set of link $l(i,j)$.

Since each mesh node has a single radio, it either transmits or receives on all the occupied subchannels in the same time slot. Thus, for a certain link $l(i,j)$, we have the following *transmitting* and *receiving constraint* (i.e., *Tx/Rx constraint*):

$$\begin{aligned} X(i,j,t,s) \times \Bigg[& X(i,j,t,s) + \sum_{f=1}^{W} \sum_{p \in \mathrm{in}(i)} X(p,i,t,f) \\ & + \sum_{g=1}^{W} \sum_{q \in \mathrm{out}(j)} X(j,q,t,g) \Bigg] \leq 1 \\ \forall l(i,j) \in A \qquad & \forall t = 1, 2, \ldots, T \qquad \forall s = 1, 2, \ldots, W \end{aligned} \tag{5}$$

where $\mathrm{in}(i)$ is a set of nodes that send data to node i. Similarly, $\mathrm{out}(j)$ is the set of nodes that receive data from node j.

Finally, to satisfy the traffic demand of each link $l(i,j) \in A$, we need to consider the *traffic demand constraint*

$$\begin{aligned} & \sum_{t=1}^{T} \sum_{s=1}^{W} X(i,j,t,s) \geq D(i,j) \\ & D(i,j) \in \{1, 2, \ldots, M\} \end{aligned} \tag{6}$$

where $D(i,j)$ represents the units of traffic demand on link $l(i,j)$. This constraint means that each link must be assigned with enough time slots and subchannels to support its traffic demand.

Consequently, we have formulated the optimization problem of time slot and subchannel allocation for OFDMA-based channel-width adaptation. We call this problem the single-radio OFDMA-based resource-allocation (SRORA) problem. In summary, SRORA needs to optimize the objective in (1), subject to constraints in (2)–(6). In the following theorem, we prove that SRORA is NP-complete.

IEEE Proof

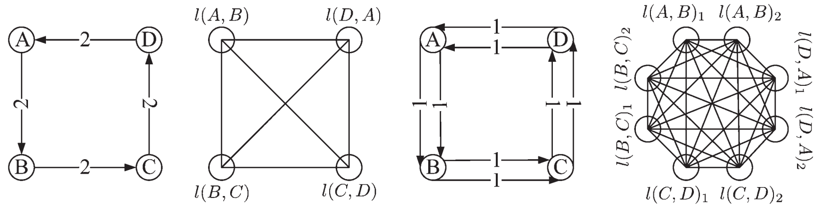

Fig. 2. (a) Communication graph $G(V, A)$, which consists of four directional communication links. Each link has 2 units of traffic demands. Based on the protocol interference model, $G(V, A)$ is converted into the interference graph G' in (b), where each vertex represents a directional communication link in $G(V, A)$. (c) Split communication graph of $G(V, A)$. It is constructed by splitting a communication link in $G(V, A)$ into several links, each with one unit of traffic demand, e.g., $l(A, B)$ in $G(V, A)$ has two units of traffic demands; hence, it is split into $l(A, B)_1$ and $l(A, B)_2$ in G_{split}, each with one unit of traffic demand. (d) Interference graph of the split communication graph G_{split}. (a) $G(V, A)$. (b) G'. (c) G_{split}. (d) G'_{split}.

Theorem 1: In SRORA, the decision problem of verifying whether K time slots are enough to satisfy the total traffic demands is NP-complete.

Proof: First, for any candidate solution of time slot and subchannel allocation, whether all the constraints are satisfied can be verified in polynomial time. Thus, the decision problem in SRORA is NP. Second, we consider the special case of SRORA by setting $W = 1$ and $D(i, j) = 1$ for all links. Using the protocol interference model, we convert the directional link $l(i, j) \in A$ in the communication graph $G(V, A)$ into the vertex in the corresponding interference graph G', as shown in Fig. 2. Based on the interference graph G', each link $l(i, j)$ in the communication graph $G(V, A)$ can construct an interference set $I_{l(i,j)}$. Since in this special case only one subchannel and one unit of traffic demand are considered for each link, only one time slot is needed in a frame to satisfy *traffic demand constraint* (6). To satisfy *link interference constraint* (4), any link in $I_{l(i,j)}$ must be assigned a different time slot from that of link $l(i, j)$. In this special case, when *link interference constraint* (4) is satisfied, Tx/Rx *constraint* (5) is also automatically satisfied due to the two facts: 1) The links $l(p, i)$ where $p \in \mathrm{in}(i)$ and links $l(j, q)$ where $q \in \mathrm{out}(j)$ are in set $I_{l(i,j)}$; and 2) the link in $I_{l(i,j)}$ is assigned with a different time slot from the link $l(i, j)$. Therefore, the problem of determining whether K time slots are enough to support the traffic demands of all links in the communication graph $G(V, A)$ is equivalent to the problem of checking whether K colors are sufficient to color the vertices in the corresponding interference graph G'. We know that the latter problem is NP-complete [21], which means that every problem in NP is reducible to the decision problem of SRORA in polynomial time. As a result, the decision problem of SRORA (in the special case) is NP-complete. In the general case (with W subchannels and $D(i, j)$ traffic demand), the decision problem is also NP-complete. □

B. Greedy Algorithm

Since the problem SRORA is NP-complete, a low-complexity greedy algorithm is proposed for the SRORA problem, and we call it GR-SRORA. In our greedy algorithm, links are assigned with time slot and subchannel in a certain sequential order just like coloring the vertices in the corresponding interference graph. However, here we also need to consider Tx/Rx *constraint*.

GR-SRORA is described in Algorithm 1. It works as follows.

1) Lines 2–15 specify the procedures of assigning the time slot and subchannel to link $l(i, j)$ considering both *link interference constraint* and Tx/Rx *constraint*. The resource-allocation status table of link $l(i, j)$, denoted by $\Phi(i, j, t, s)$, captures *link interference constraint*. More specifically, for any t and s, if $\Phi(i, j, t, s) = 1$, it means that subchannel s in time slot t is occupied by a link in the interference set of link $l(i, j)$ (i.e., $I_{l(i,j)}$). The single-radio OFDMA constraint table of link $l(i, j)$, denoted by $\Psi(i, j, t)$, captures Tx/Rx *constraint*. More specifically, for any t, if $\Psi(i, j, t) = 1$, it means that link $l(i, j)$ cannot transmit on any subchannel in time slot t.
2) Lines 16–19 are executed after a link assignment. Two tables ($\Phi(p, q, t, s)$ and $\Psi(p, q, t)$) of each link are updated and will be used in the next link assignment.
3) Line 21 is used to determine T_{greedy}, which is the total number of time slots consumed by the network following the greedy algorithm.

The performance of the greedy algorithm GR-SRORA is analyzed as follows. We denote the minimum number of time slots consumed in SRORA and the greedy algorithm GR-SRORA as T_{optimal} and T_{greedy}, respectively. Based on the split graph G_{split} of the original communication graph $G(V, A)$ and the split interference graph G'_{split} in Fig. 2, the relationship between T_{optimal} and T_{greedy} is shown in Theorem 2.

Algorithm 1 GR-SRORA

Input:
- Communication graph $G(V, A)$
- Resource consumption status table of link $l(i, j)$: $\Phi(i, j, t, s)$
- Single-radio OFDMA constraint table of link $l(i, j)$: $\Psi(i, j, t)$
- Traffic demand on link $l(i, j)$: $D(i, j)$
- Number of total subchannels: W

Output:
- Network time slot consumption: T_{greedy}
- The maximum time slot assigned to link $l(i, j)$: $T_{l(i,j)}$
- Time slot and subchannel allocation result for link $l(i, j)$: $X(i, j, t, s)$

IEEE Proof

Initialization:

- $\Phi(i,j,t,s) = 0$
- $\Psi(i,j,t) = 0$
- $T_{\text{greedy}} = 0$
- $T_{l(i,j)} = 0$

1: **for all** $l(i,j) \in A$ **do**
2: **for** $t = 1$ to $+\infty$ **do**
3: **if** $D(i,j) == 0$ **then**
4:   Break;
5: **end if**
6: **if** $\Psi(i,j,t)! = 1$ **then**
7:   **for** $s = 1$ to W **do**
8:    **if** $D(i,j) > 0$ && $\Phi(i,j,t,s) == 0$ **then**
9:     $X(i,j,t,s) = 1$
10:    $D(i,j) = D(i,j) - 1$
11:    $T_{l(i,j)} = t$
12:   **end if**
13: **end for**
14: **end if**
15: **end for**
16: **for all** $l(p,q) \in A$ **do**
17: Update $\Phi(p,q,t,s)$
18: Update $\Psi(p,q,t)$
19: **end for**
20: **end for**
21: $T_{\text{greedy}} = \max_{l(i,j)\in A} T_{l(i,j)}$
22: **Stop**.

Theorem 2: For the optimal solution of the problem SRORA T_{optimal} and the greedy solution of GR-SRORA T_{greedy}, $\lceil(\chi(G'_{\text{split}})/W)\rceil \le T_{\text{optimal}} \le T_{\text{greedy}} \le T_{\max} = \delta(G'_{\text{split}})+1$, where $\lceil\cdot\rceil$ is the ceiling function, $\delta(\cdot)$ is the maximum degree of a graph, and $\chi(\cdot)$ is the chromatic number of a graph. Moreover, G'_{split} is the interference graph constructed by splitting a communication link in $G(V,A)$ into separate links, each with one unit traffic demand. AQ2

Proof: The proof consists of two parts. First, we derive the lower bound of T_{optimal} by looking into the property of T_{optimal}. In the communication graph $G(V,A)$, each directional link $l(i,j)$ (with traffic demand $D(i,j)$) is split into $D(i,j)$ virtual directional links between node i and node j to construct the split communication graph G_{split}, as shown in Fig. 2(c). Based on the protocol interference model, the split communication graph G_{split} is converted into its corresponding interference graph G'_{split}, as shown in Fig. 2(d). If each vertex of G'_{split} is greedily colored, i.e., assigning different time slot–subchannel pairs to interfering virtual links G_{split}, then each link in communication graph $G(V,A)$ certainly satisfies the *link interference constraint*. The minimum number of colors (i.e., time slot–subchannel pairs) that G'_{split} consumes is the chromatic number $\chi(G'_{\text{split}})$ [22]. Since W subchannels are available for each time slot, the minimum number of consumed time slots becomes $\lceil(\chi(G'_{\text{split}})/W)\rceil$, when only *link interference constraint* is taken into account. However, in SRORA, there exists the Tx/Rx *constraint*; hence, the optimal number of time slots (i.e., T_{optimal}) must be larger than or equal to $\lceil(\chi(G'_{\text{split}})/W)\rceil$. In other words, $\lceil(\chi(G'_{\text{split}})/W)\rceil \le T_{\text{optimal}}$ holds.

Second, we derive the upper bound of T_{optimal} by exploring the property of T_{greedy}. We consider the worst case where there exists only one subchannel (i.e., $W = 1$). Given any link assignment order $\vec{\mathcal{L}}$ taken by GR-SRORA, there exists a corresponding greedy coloring order in G'_{split}. For any greedy coloring order in G'_{split}, the number of colors that are needed is at most $\delta(G'_{\text{split}}) + 1$ [23]. Since the number of colors in G'_{split} is exactly equal to the number of time slots needed in the worst case communication graph, i.e., $T^{\text{worst}}_{\text{greedy}}(\vec{\mathcal{L}})$, thus, for any link AQ3 assignment order $\vec{\mathcal{L}}$, the number of time slots that are consumed is upper bounded by $T_{\max} = \delta(G'_{\text{split}}) + 1$. In general, the number of subchannels W is usually a constant greater than 1. Thus, for any link assignment order $\vec{\mathcal{L}}$, the total number of time slots needed by GR-SRORA $T_{\text{greedy}}(\vec{\mathcal{L}})$ is equal or smaller than $T^{\text{worst}}_{\text{greedy}}(\vec{\mathcal{L}})$. Thus, $T_{\text{greedy}} \le T_{\max} = \delta(G'_{\text{split}}) + 1$.

Combining the lower bound and the upper bound, we have $\lceil(\chi(G'_{\text{split}})/W)\rceil \le T_{\text{optimal}} \le T_{\text{greedy}} \le T_{\max} = \delta(G'_{\text{split}})+1$, which proves Theorem 2. □

The complexity of the GR-SRORA is analyzed as follows. In GR-SRORA, the number of links L is a variable, but subchannel number W and traffic demand upper bound M for each link are constants. In Algorithm 1, lines 2–15 are for assigning time slots and subchannels to link $l(i,j)$. Its complexity is $\mathcal{O}(T_{\max})$, where $T_{\max}$ is the upper bound of T_{greedy}. As shown in Theorem 2, $T_{\max} = \delta(G'_{\text{split}}) + 1$. Since $\delta(G'_{\text{split}}) + 1 \le M \times L + 1$, hence, $T_{\max} \le M \times L + 1$. Thus, the complexity from lines 2–15 is $\mathcal{O}(L)$. Lines 16–19 are to update $\Phi(i,j,t,s)$ and $\Psi(i,j,t)$. The complexity is $\mathcal{O}(L)$. Thus, considering lines 1–22, the complexity is $L \times (\mathcal{O}(L) + \mathcal{O}(L))$. Therefore, the total complexity is $\mathcal{O}(L^2)$.

C. GA

Since the greedy algorithm, i.e., GR-SRORA, usually can only obtain the suboptimal solution, we adopt a GA to obtain a near-optimal result as a theoretical reference for our greedy algorithm.

To apply the GA, the number of decision variables $X(i,j,t,s)$ in the optimization problem SRORA needs to be constant. Since for a certain network the number of links L and the number of subchannels W are constants, we also need to fix the total time slots for assignment so that the number of $X(i,j,t,s)$ will be fixed. From the proof of Theorem 2, T_{optimal} is upper bounded by $T_{\max} = \delta(G'_{\text{split}}) + 1$ for a given communication graph $G(V,A)$. With this bound, the problem SRORA is reformulated as follows:

$Minimize\ T.$

$$\text{s.t.} \begin{cases} X(i,j,t,s) + X(p,q,t,s) \le 1 \\ \Big[X(i,j,t,s) + \sum_{f=1}^{W}\sum_{p\in \text{in}(i)} X(p,i,t,f) \\ \quad + \sum_{g=1}^{W}\sum_{q\in \text{out}(j)} X(j,q,t,g)\Big] \times X(i,j,t,s) \le 1 \\ \sum_{t=1}^{T_{\max}}\sum_{s=1}^{W} X(i,j,t,s) \ge D(i,j) \\ X(i,j,t,s) \in \{0,1\} \\ \forall l(i,j) \in A \qquad \forall s = 1,2,\ldots,W \\ \forall l(p,q) \in I_{l(i,j)} \qquad \forall t = 1,2,\ldots,T_{\max}. \end{cases}$$

IEEE Proof

The objective T is the maximum occupied time slot in the network and is calculated with decision variable $X(i,j,t,s)$ as $T = \max_{t\in\{1,2,\ldots,T_{\max}\}} t$, subject to $\max_{l(i,j)\in A, s\in\{1,2,\ldots,W\}} X(i,j,t,s) \neq 0$. The previous optimization problem is exactly the same as SRORA, except that the range of t is upper bounded by $T_{\max}$ instead of T. Thus, its complexity is the same as SRORA, i.e., it is also NP-complete.

Based on this new formulation, a GA is developed for SRORA. We call it GA-SRORA. Different from classic optimization methods such as gradient-based approaches, GA is well suited for integer programming problems. Although there is no absolute guarantee for the GA-SRORA to obtain an optimal solution, the algorithm can be executed for sufficient time to reach a near-optimal solution.

GA evolves its generation into the next generation via three essential steps: reproduction, crossover, and mutation. Thus, GA-SRORA is executed according to the following steps.

1) Initialize Population: The population of our algorithm GA-SRORA consists of chromosomes. Each chromosome is represented by $X(i,j,t,s)$ of all links.
2) Evaluation and Fitness Assignment: For every chromosome, its fitness needs to be minimized in GA-SRORA. The fitness captures the objective function and the constraints in the reformulated SRORA problem. As a result, the fitness is described as

$$
\begin{aligned}
&Fitness \\
&\quad = T + P \times (C_1 + C_2 + C_3) \\
&C_1 = \sum_{l(i,j)\in A} \max\left[0, 1 - \sum_{t=1}^{T_{\max}} \sum_{s=1}^{W} X(i,j,t,s)/D(i,j)\right] \\
&C_2 = \sum_{l(i,j)\in A} \sum_{l(p,q)\in I_{l(i,j)}} \sum_{t=1}^{T_{\max}} \sum_{s=1}^{W} \max \\
&\qquad \times [0, X(i,j,t,s) + X(p,q,t,s) - 1] \\
&C_3 = \sum_{l(i,j)\in A} \sum_{t=1}^{T_{\max}} \sum_{s=1}^{W} \max \\
&\qquad \times \left[0, \left(X(i,j,t,s) + \sum_{f=1}^{W} \sum_{p\in \mathrm{in}(i)} X(p,i,t,f)\right.\right. \\
&\qquad\qquad \left.\left. + \sum_{g=1}^{W} \sum_{q\in \mathrm{out}(j)} X(j,q,t,g)\right) X(i,j,t,s) - 1\right]
\end{aligned}
$$

where T is the maximum occupied time slot in the network and is obtained with $X(i,j,t,s)$, P as a penalty parameter. C_1, C_2, and C_3 are derived from *traffic demand constraint*, *link interference constraint*, and Tx/Rx *constraint*, respectively.
3) Reproduction: According to the fitness, better chromosomes are copied and worse chromosomes are removed, whereas holding population size constant. A fair selection is applied to generate "winners" and put them into the "mating pool."
4) Crossover: Parent chromosomes swap a subset of their strings, generating two new chromosomes called children.
5) Mutation: A new chromosome is generated by changing value of one bit in its string. This step reduces the chance of falling into the local optimal point.
6) Steps 2–5 are repeated for U rounds to obtain a relatively stable solution.

The complexity of the GA-SRORA can be derived similarly to Algorithm 1. For iteration rounds U, population size V, and link number L, the complexity of GA-SRORA is $\mathcal{O}(UVL^3)$.

IV. Distributed Medium Access Control for Orthogonal Frequency-Division Multiple-Access-Based Channel-Width Adaptation

Here, a distributed MAC protocol is designed based on the greedy algorithm for OFDMA-based channel-width adaptation.

A. *Distributed Operation of the Greedy Algorithm*

Four information tables are maintained by every node i: 1) $Q_{\mathrm{in}}(i,p,q)$, which indicates whether subchannel q in time slot p is occupied by a receiving link (i.e., incoming link) of a node in the interference range of node i; 2) $Q_{\mathrm{out}}(i,p,q)$, which indicates whether subchannel q in time slot p is occupied by a sending link (i.e., outgoing link) of a node in the interference range of node i; 3) $O_{\mathrm{in}}(i,t)$, which indicates whether time slot t is occupied by any receiving link of node i; and 4) $O_{\mathrm{out}}(i,t)$, which indicates whether time slot t is occupied by any sending link of node i. How such information is collected is explained in Section IV-C and D.

For a given link $l(i,j)$, sending node i is responsible for assigning time slots and subchannels to support a given number of units (denoted as $D(i,j)$) in a TDMA frame. With these variables, resource allocation of link $l(i,j)$ is executed as follows.

1) Information fusion: Based on the protocol interference model, any receiving link of a node located in the interference range of node i or any sending link of a node located in the interference range of node j potentially interferes with link $l(i,j)$; hence, node i needs to communicate with node j to collect all the resource-allocation information by combining tables $Q_{\mathrm{in}}(i,p,q)$ and $Q_{\mathrm{out}}(j,p,q)$ before resource allocation is conducted. Due to the single-radio OFDMA Tx/Rx *constraint*, node i also needs to obtain table $O_{\mathrm{out}}(j,t)$ from node j, and then determines which time slot is still available by checking $O_{\mathrm{in}}(i,t)$ and $O_{\mathrm{out}}(j,t)$.
2) Time slot and subchannel allocation: For the first time slot, node i assigns the unoccupied subchannels to link $l(i,j)$ to support the traffic demands. If the first time slot is not enough, it goes to the second time slot. This process is repeated until the sum of the assigned subchannels can support the traffic demand of link $l(i,j)$. During this period, any link $l(p,q) \in I_{l(i,j)}$ (i.e., $l(p,q)$ is any receiving link of a node located in the interference range of node i or any sending link of a node located in the interference range of node j) cannot conduct resource allocation simultaneously.

IEEE Proof

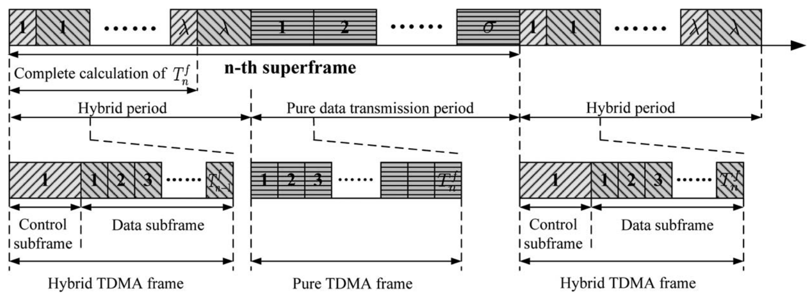

Fig. 3. Frame structure.

3) Information table update: After resource allocation of link $l(i, j)$, all nodes in the interference range of node i and node j update their information tables immediately.

To support the aforementioned mechanisms, the control messages need to be received within the interference range. To this end, the lowest transmission rate is adopted by control messages.

Since every node contends to assign resources to its outgoing links in a greedy way, two nodes that are far away enough can conduct resource allocation simultaneously. As a result, resource allocation in the entire WMN is conducted in a distributed way and is thus called distributed GR-SRORA (DGR-SRORA). Based on this distributed resource-allocation process, a distributed multisubchannel TDMA MAC protocol is developed in the following sections.

B. Frame Structure

The new MAC protocol works in a hybrid way, as shown in Fig. 3. In each superframe, a new resource allocation is carried out in λ control subframes, and data transmissions proceed on the assigned time slots and subchannels.

A superframe includes two parts, namely, hybrid period and pure data transmission period. The hybrid period consists of λ hybrid TDMA frames, where λ is a constant and must be set large enough for all the nodes to complete resource allocation. A hybrid TDMA frame is composed of two subframes: control subframe and data subframe. Each consists of a number of time slots. The control subframe is used for resource allocation. The data subframe is used for data transmission. The pure data transmission period consists of σ pure TDMA frames, where σ is a constant. These TDMA frames are only used for data transmission.

As shown in Fig. 3, in the nth superframe, the length of the data subframe in the hybrid period is T_{n-1}^f, which is determined in the $(n-1)$-th superframe. In the hybrid period of the nth superframe, our resource-allocation algorithm determines a new length of a TDMA frame T_n^f. This new value updates the length of a pure TDMA frame in the pure data transmission period of the nth superframe. It also determines the length of the data subframe in the hybrid period of the $(n+1)$-th superframe. As a result, in Fig. 3, the frame lengths in the left hybrid TDMA frame and the right hybrid TDMA frame are equal to T_{n-1}^f and T_n^f, respectively.

In the control subframe of the hybrid period, each node uses an request-to-send/clear-to-send mechanism to contend for time slots' and subchannels' allocation. In all TDMA frames for data transmission, each node adopts carrier-sense multiple access/collision avoidance to access the assigned time slots and subchannels. This can prevent collisions due to allocation error or out-of-network interference. As a result, our MAC protocol is actually a *TDMA MAC overlaying CSMA/CA*.

C. Distributed Resource-Allocation Procedure

The control subframe in Fig. 3 is used to signal distributed resource allocation. Control messages are sent with the lowest transmission rate using all subchannels. For resource assignment of link $l(i, j)$, the negotiation between node i and node j follows this procedure.

1) Node i sends a request-to-assign (RTA) packet to node j. All nodes except node j in the sensing range of node i keep quiet.
2) Upon receiving the RTA packet, node j sends node i a clear-to-assign (CTA) packet, which contains $Q_{\text{out}}(j, p, q)$ and $O_{\text{out}}(j, t)$. All nodes except node i in the sensing range of node j keep quiet.
3) Upon receiving the CTA packet, node i relies on tables $Q_{\text{in}}(i, p, q)$, $Q_{\text{out}}(j, p, q)$, $O_{\text{in}}(i, t)$, and $O_{\text{out}}(j, t)$ to assign time slots and subchannels to link $l(i, j)$. Then, node i broadcasts an announcement (ANN) packet, which contains the assignment result for link $l(i, j)$, to all nodes in its interference range.
4) Upon receiving the ANN packet, all nodes in the interference range of node i update their tables. Node j also broadcasts an ANN packet to all nodes in its interference range, and then such receiving nodes update their information tables.

An example of resource-allocation procedure is explained next. The signaling messages are transmitted in the lowest rate to cover all the nodes in the interference range, and the exchange procedure is shown in Fig. 4.

1) Node A starts to assign time slots and subchannels for link $l(A, B)$. It broadcasts an RTA packet to node B. Node C and node D can receive the signaling packet; hence, they keep quiet.
2) Node B receives the RTA packet and then broadcasts a CTA packet, which contains $Q_{\text{out}}(B, p, q)$ and $O_{\text{out}}(B, t)$, to node A. Nodes A and C can receive this packet, but node D can only sense it.
3) Node A receives the CTA packet and broadcasts an ANN packet, which contains the assignment result for link $l(A, B)$. Node B receives this packet, but nodes C and D can only sense it.

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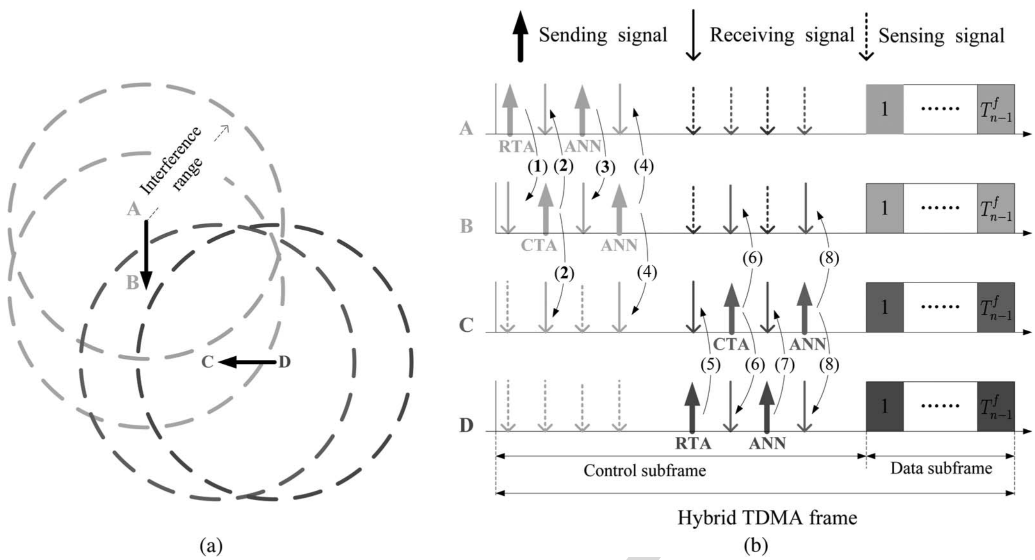

Fig. 4. Operation of the MAC protocol: An example. (a) Topology. (b) Resource negotiation.

4) When node B receives the ANN packet, it updates its own information tables and rebroadcasts the ANN packet. Nodes A and C receive it and update their tables, but node D can only sense it.
5) Node D starts to assign time slots and subchannels for link $l(D, C)$. It broadcasts an RTA packet to node C. Node A and node B can sense the signaling; hence, they keep quiet.
6) Node C receives the RTA packet and then broadcasts a CTA packet, which contains $Q_{\text{out}}(C, p, q)$ and $O_{\text{out}}(C, t)$, to node D. Node D and node B can receive this packet, but node A can only sense it.
7) Node D receives the CTA packet and broadcasts an ANN packet, which contains the allocation result of link $l(D, C)$. Node C receives this packet, but node A and node B can only sense it.
8) When node C receives the ANN packet, it updates its own information tables and rebroadcasts the ANN packet. Nodes D and B receive it and update their information tables, but node A can only sense it.

In the distributed algorithm, every node determines its own time slot. Thus, the largest time slot in one node may be different from that of another node. To avoid inconsistent TDMA frame in different links, the largest time slot in the allocation must be known to all nodes. This can be done by the following simple procedure. When a node gets resource-allocation information from another node, it compares its largest time slot with that in the allocation information. If its own value is smaller, it needs to update its largest time slot number and broadcast the updated information to its neighbors; otherwise, no action is needed.

D. Enhancement for Multiple Interference Domains

The aforementioned protocol is effective for the single interference domain because every time only one link is in the resource-allocation process and other nodes can hear signaling messages and keep quiet. However, in the case of multiple interference domains, there exist collisions in ANN packets. For example, in Fig. 5, node B and node F successfully make reservation for link $l(B, A)$ and link $l(F, G)$ by exchanging RTA and CTA packets. However, it is possible that the ANN packets broadcast by node B and node F simultaneously and interfere each other at node D. Thus, node D cannot receive the ANN packet, which leads to errors in the following resource assignment in other links. To reduce the probability of collisions in ANN packets, we propose a scheme as follows. During the resource-allocation process of link $l(i, j)$, node i and node j exchange RTA and CTA packets as usual. The process of broadcasting ANN packets is modified to reduce the collision probability: 1) Node i and node j broadcast ANN packets in turn for K_{ANN} rounds instead of only one round; and 2) before broadcasting an ANN packet, the sending node randomly chooses a waiting time in the backoff window W_{ANN} and delays the ANN packet transmission for the chosen waiting time.

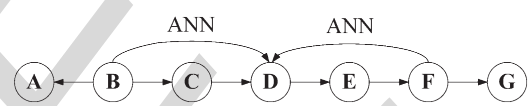

Fig. 5. ANN packet collision may occur in the case of multiple interference domains.

Although this scheme cannot guarantee collision-free ANN packets, the collision probability dramatically drops with the increased K_{ANN} and W_{ANN}. It should be noted that how to design an effective distributed MAC protocol in multiple interference domains still remains a challenging problem.

V. Performance Results

Here, MATLAB simulations are carried out to evaluate our algorithms and protocols developed in previous sections. Since the objective of our algorithms and protocols is to leverage channel-width adaptation to efficiently support diverse traffic demands in different links of a WMN, transmission rate in different links is assumed to be homogeneous. Performance results from such a setting provide a better demonstration about

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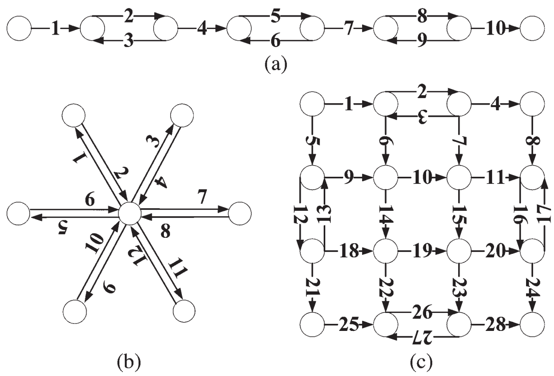

Fig. 6. Simple topologies.

how channel-width adaptation improves throughput; the impact from heterogeneous link rates is eliminated. In simulations, the homogeneous link rate is equal to 54 Mb/s when the bandwidth is 20 MHz. The total available bandwidth is 40 MHz; hence, the corresponding link rate using a whole spectrum is 108 Mb/s. Moreover, a single radio is considered in each mesh node.

In our OFDMA-based channel-width adaptation scheme, the whole spectrum is divided into 64 subchannels and the length of a time slot is 5 ms. We assume that one subchannel per time slot can transmit 1 unit of traffic demand. If a link is assigned two subchannels every three time slots, then its throughput is $(2/3) \times (108/64) = 1.125$ Mb/s. The network throughput is defined as the ratio of the total supported traffic demands over the length of a TDMA frame.

To fully evaluate our algorithm and protocols, different network topologies are considered in the following sections. The details of network setup and the corresponding traffic demands are specified separately for each topology.

A. Simple Topologies

The greedy algorithm and GA are evaluated under three simple topologies in Fig. 6. In each topology, the link ID is marked in the figure, and all the links have the same length, which represents the communication range. The interference range is set twice the communication range.

For each link, the traffic demand is uniformly distributed in $\{1, \ldots, 128\}$ (units).

For each topology, we evaluate the network throughput that can be achieved in a WMN with available bandwidth of 40 MHz. The performance results of our channel-width adaptation algorithms (i.e., GR-SRORA and GA-SRORA) are compared with that achieved by the single-radio traditional channel-width adaptation (SRTCWA) scheme and also with that achieved by the single-radio fixed channel-width (SRFCW) scheme. SRTCWA and SRFCW are executed following the same procedure as GR-SRORA (i.e., greedily assign time slot and channel to all the links in the same order as GR-SRORA) but consider different constraints. In SRTCWA, there are four options of channel width (i.e., 5, 10, 20, and 40 MHz), and the center frequency of each channel can be adjusted. In SRFCW, the radio on each node uses a 20-MHz channel. To be fair in comparison, two orthogonal channels (i.e., totally 40 MHz) are available in SRFCW for parallel links in the same interference domain.

In the string topology, as shown in Fig. 7(a), on average, the network throughput of GR-SRORA is 19.2% higher than that achieved by SRTCWA and 30.8% higher than that of SRFCW. In this network structure, the throughput improvement is not significant due to lack of PMP structure in the string topology.

In the star topology, as shown in Fig. 7(b), on average, the network throughput of GR-SRORA is 54.5% higher than that of SRTCWA and 136.4% higher than that of SRFCW. The improvement is significant because our OFDMA-based channel-width adaptation scheme is very suitable for exploring channel-width adaptive concurrent transmissions in a star network structure.

In the grid topology, as shown in Fig. 7(c), on average, the network throughput of GR-SRORA is 19.3% higher than that of SRTCWA and 29.8% higher than that of SRFCW.

As shown in Fig. 7, the greedy algorithm achieves nearly the same throughput as that of the GA-based algorithm, which indicates that the greedy algorithm is effective to obtain a near-optimal solution to the channel-width adaptation problem in WMNs.

B. Randomized Topology

Our distributed MAC protocol is also evaluated in a randomized topology. The communication range of each node is 100 m, the interference range is 200 m, and the sensing range is 300 m. The RTA and CTA packets have a length of 120 bytes, and the ANN packet has a length of 30 bytes. As explained in Section IV, the lowest transmission rate is adopted to send these packets, and it is set to 6 Mb/s.

1) Single Interference Domain Scenario: In this scenario, nodes are randomly distributed within a circle with a diameter of 200 m. Since all nodes can hear each other, no collision is associated with ANN packets. The distributed MAC protocol (DGR-SRORA) in Section IV is adopted. The ANN packets are broadcast only for one round. In the simulation, six cases of node–link pairs are considered: 10 nodes 15 links, 10 nodes 20 links, 20 nodes 30 links, 20 nodes 40 links, 30 nodes 45 links, and 30 nodes 60 links. For each case, the nodes are randomly distributed and the links are randomly selected. The traffic demand for each link is uniformly distributed within $\{1, \ldots, 128\}$ (units).

a) Network throughput: In each case of node–link pair, the distributed protocol DGR-SRORA is compared with SRTCWA and SRFCW. The network throughput of each case is averaged over five tests and is shown in Fig. 8. In all cases, our OFDMA-based channel-width adaptation scheme outperforms SRTCWA and SRFCW. Moreover, compared with the SRTCWA, DGR-SRORA improves the network throughput by 14.3%, 20.0%, 18.5%, 15.0%, 13.3%, and 16.1%, respectively, in six cases. As compared with SRFCW, DGR-SRORA enhances the network throughput by 28.6%, 30.0%, 29.6%, 25.0%, 22.2%, and 24.2%, respectively, in six cases.

b) Resource-allocation delay: The total time required for the distributed resource-allocation procedure is investigated. In our simulation, the sum of the control subframe and the data

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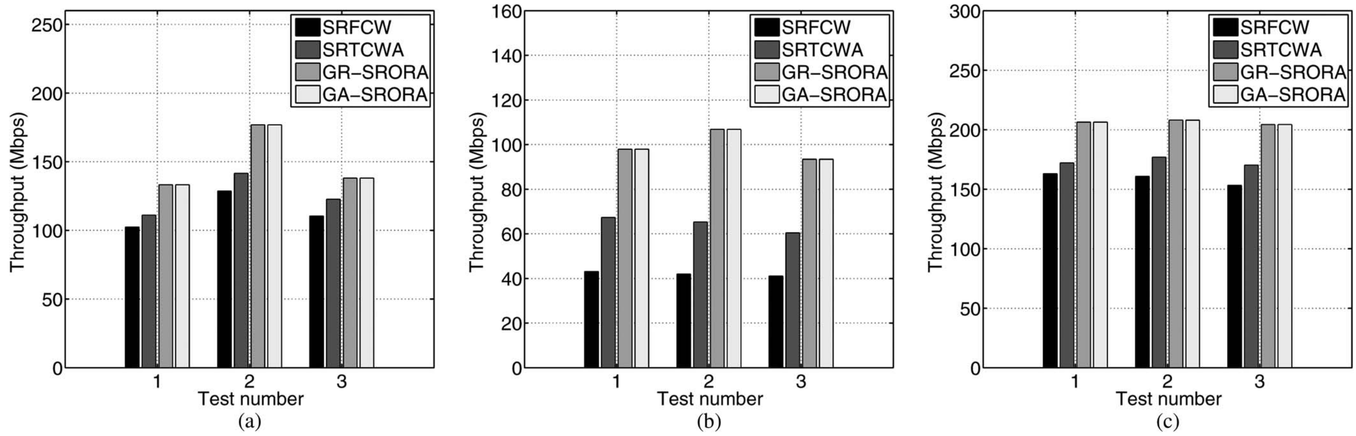


Fig. 7. Network throughput for simple topologies. (a) String topology. (b) Star topology. (c) Grid topology.

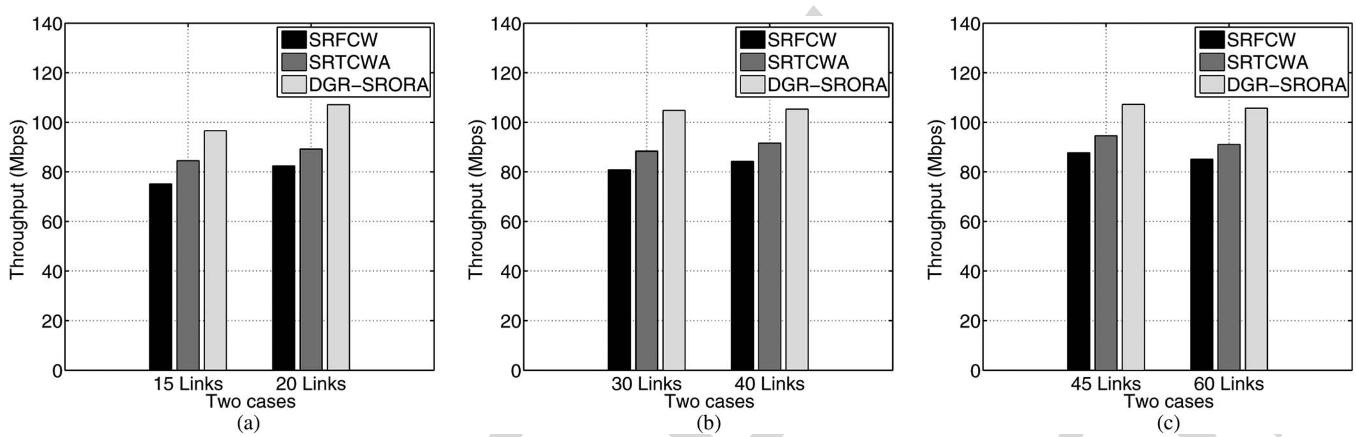


Fig. 8. Network throughput in the scenario of single interference domain. (a) 10 nodes. (b) 20 nodes. (c) 30 nodes.

TABLE I
TOTAL RESOURCE ALLOCATION TIME FOR THE SINGLE INTERFERENCE DOMAIN SCENARIO

Control Subframe	Data Subframe	Nodes: 10 Links: 15	Nodes: 10 Links: 20	Nodes: 20 Links: 30	Nodes: 20 Links: 40	Nodes: 30 Links: 45	Nodes: 30 Links: 60
20 ms	80 ms	9.2 ms	11.3 ms	18.4 ms	104.5 ms	112.1 ms	202.3 ms
15 ms	85 ms	9.2 ms	11.3 ms	103.9 ms	110.5 ms	202.4 ms	214.7 ms
10 ms	90 ms	9.2 ms	101.8 ms	200.5 ms	205.9 ms	305.7 ms	407.0 ms
5 ms	95 ms	104.0 ms	202.5 ms	304.7 ms	504.4 ms	801.5 ms	1100.5 ms

subframe (i.e., the length of a hybrid TDMA frame) is assumed to be 100 ms. For each case of node–link pair, we consider different lengths of control subframe and data subframe. The results are shown in Table I. For each case of node–link pair, when the control subframe is longer, the allocation delay is smaller. Thus, if we need a faster allocation procedure, a larger control subframe is necessary, which leads to more overhead in signaling. However, even if the overhead is less than 10% for signaling, the allocation can be done within 1 s for node–link pairs: 10–15, 10–20, 20–30, 20–40, and 30–45. Such a fast allocation procedure means that our MAC protocol is highly adaptive to dynamic network conditions such as topology change or traffic variations.

Scenario of Multiple Interference Domains: In this scenario, 50 nodes are randomly distributed in a square whose side length is 1000 m, as shown in Fig. 9. The distributed MAC protocol with modified ANN packet transmission in Section IV

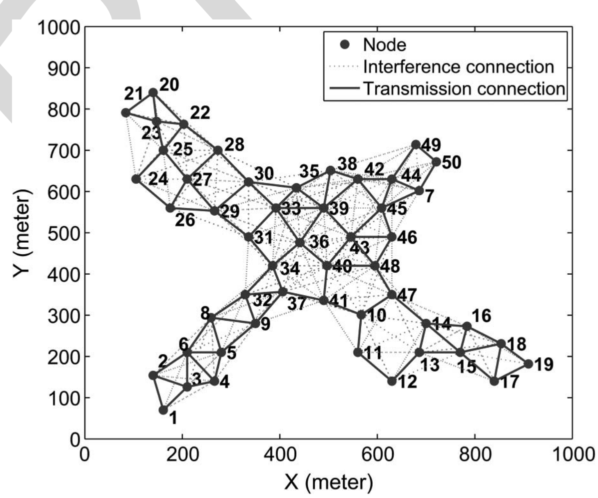
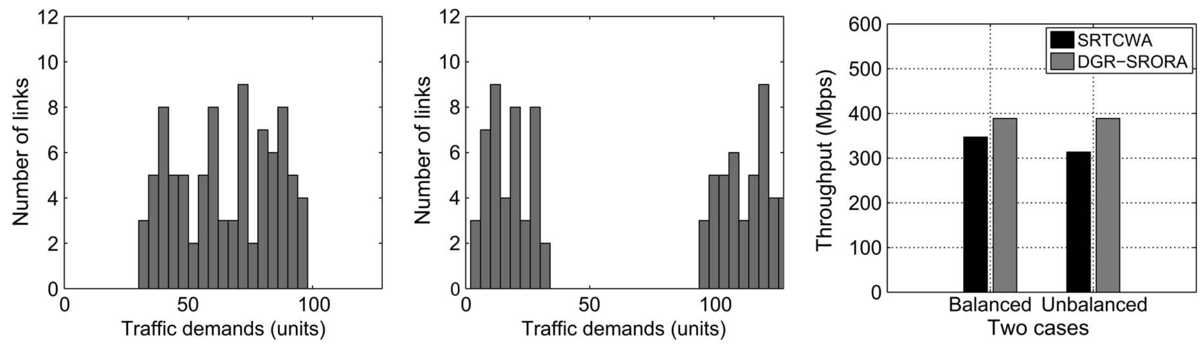
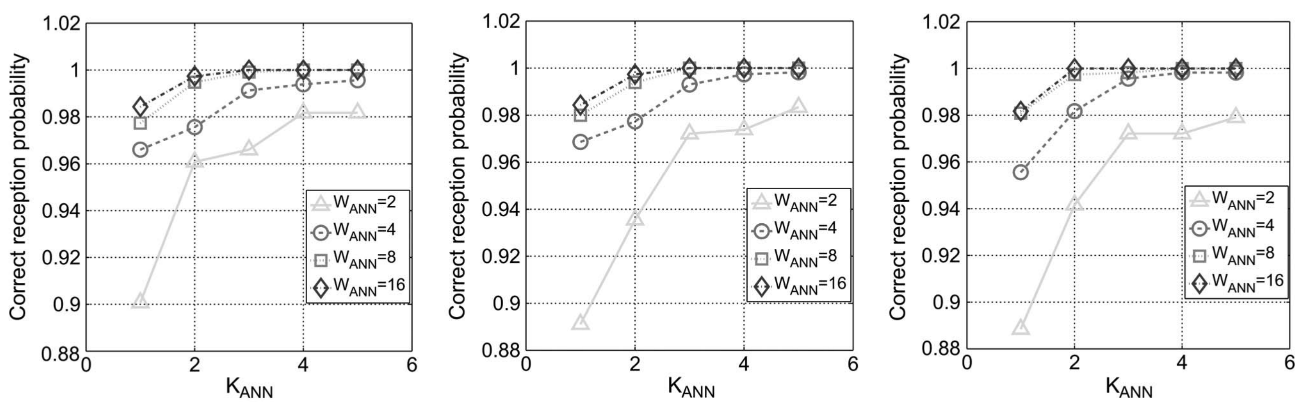


Fig. 9. Topology.



(a) (b) (c)

Fig. 10. Network throughput under different traffic distributions. (a) Balanced traffic distribution. (b) Unbalanced traffic distribution. (c) Network throughput.



(a) (b) (c)

Fig. 11. ANN packet reception probability in the network with multiple interference domains. (a) Control subframe: 10 ms. (b) Control subframe: 15 ms. (c) Control subframe: 20 ms.

is adopted. In this protocol, the ANN packets are broadcast after a randomly chosen waiting time for several rounds.

c) Network throughput: The impact of the traffic distribution to the network throughput is illustrated in Fig. 9. Since there exists multiple interference domains, the distributed protocol DGR-SROTSA may have allocation error due to collision in ANN packets. Thus, we properly choose broadcasting rounds and backoff window to reduce collisions. We randomly choose 88 links in Fig. 9 for the test. Two cases with different traffic distributions are considered. In the first case, the traffic demand of each link is balanced and is uniformly distributed in $\{32, \ldots, 96\}$, as shown in Fig. 10(a). In the second case, the traffic demand of each link is unbalanced and is uniformly distributed in either {1, 32} or {96, 128}, as shown in Fig. 10(b). The network throughputs of these two cases are shown in Fig. 10(c). As compared with the traditional channel-width adaptation scheme (i.e., SRTCWA), our MAC protocol with OFDMA-based channel-width adaptation improves the network throughput by 12% and 24%, respectively, in these two cases. Higher throughput improvement is achieved in the case of unbalanced traffic distribution because our MAC protocol leverages OFDMA-based channel-width adaptation to allocate resource in more proper way.

d) Performance of the modified ANN packet broadcasting mechanism: In Section IV-D, we propose that an ANN packet is broadcast after a randomly selected waiting time for several rounds to reduce the collision probability. In this experiment, this mechanism is investigated with respect to different broadcasting rounds K_{ANN} and backoff window W_{ANN}. In Fig. 9, we randomly choose 88 links for testing. Three cases (with 10-, 15-, and 20-ms control subframes) are considered. In each case, the number of broadcasting rounds K_{ANN} varies from 1 to 5, and the broadcasting delay is randomly chosen in the backoff window W_{ANN}. W_{ANN} is set 2, 4, 8, and 16 (the unit is the transmission time of an ANN packet), respectively. The reception probability of ANN packets is defined as the ratio of the correctly received ANN packets over total transmitted ANN packets. In Fig. 11, for the fixed K_{ANN} in all cases, the correct reception probability is higher with larger W_{ANN}. Similarly, for the fixed W_{ANN}, the correct reception probability increases with a larger K_{ANN}. In each case, when $K_{\mathrm{ANN}} = 3$ and $W_{\mathrm{ANN}} = 16$ or when $K_{\mathrm{ANN}} = 4$ and $W_{\mathrm{ANN}} = 8$, the reception probability near reaches 1.

e) Resource-allocation delay: The total delay required for the distributed resource-allocation procedure is also investigated. In our simulation, the sum of the control subframe and the data subframe is assumed to be 100 ms, and three cases (with 10-, 15-, and 20-ms control subframes) are considered. The results are shown in Table II. When the control subframe is longer, the allocation delay is smaller. Thus, if we need a faster

TABLE II
TOTAL RESOURCE ALLOCATION DELAY FOR THE SCENARIO OF MULTIPLE INTERFERENCE DOMAINS

Rounds	$W_{ANN}(10ms)^a$				$W_{ANN}(15ms)^b$				$W_{ANN}(20ms)^c$			
	2	4	8	16	2	4	8	16	2	4	8	16
K_{ANN}=1	$0.20s$	$0.31s$	$0.50s$	$1.01s$	$0.11s$	$0.20s$	$0.31s$	$0.51s$	$0.10s$	$0.11s$	$0.21s$	$0.41s$
K_{ANN}=2	$0.21s$	$0.40s$	$0.71s$	$1.21s$	$0.20s$	$0.21s$	$0.41s$	$0.81s$	$0.11s$	$0.20s$	$0.31s$	$0.52s$
K_{ANN}=3	$0.31s$	$0.50s$	$0.91s$	$1.70s$	$0.20s$	$0.30s$	$0.51s$	$1.11s$	$0.12s$	$0.21s$	$0.40s$	$0.71s$
K_{ANN}=4	$0.40s$	$0.60s$	$1.21s$	$2.70s$	$0.21s$	$0.40s$	$0.61s$	$1.51s$	$0.20s$	$0.30s$	$0.51s$	$0.90s$
K_{ANN}=5	$0.50s$	$0.70s$	$1.31s$	$3.30s$	$0.30s$	$0.41s$	$0.80s$	$1.70s$	$0.21s$	$0.31s$	$0.52s$	$1.10s$

[a] The length of the control subframe is 10 ms
[b] The length of the control subframe is 15 ms
[c] The length of the control subframe is 20 ms

allocation procedure, a larger control subframe is necessary, which leads to more overhead in signaling. In each case, for a fixed K_{ANN}, the allocation delay becomes larger as W_{ANN} increases. Similarly, for a fixed W_{ANN}, the allocation delay grows as K_{ANN} increases. For $K_{\text{ANN}} = 3$ and $W_{\text{ANN}} = 16$, the maximum resource-allocation delay among three cases is 1.70 s (i.e., in the 10 ms control subframe case). For $K_{\text{ANN}} = 4$ and $W_{\text{ANN}} = 8$, the maximum resource-allocation delay among three cases is 1.21 s (i.e., in the 10 ms control subframe case). Therefore, with 10% signaling overhead (due to the control subframe), the reception probability reaches 1 with a resource-allocation delay of less than 2 s.

VI. CONCLUSION

In WMNs, there always exists a mismatch between link capacity and traffic demand. In this paper, an OFDMA-based channel-width adaptation mechanism has been designed to alleviate such a mismatch of each link in WMNs. It was formulated as a time slot and subchannel allocation problem and was proved to be NP-complete. Thus, a greedy algorithm and a GA were derived to obtain a suboptimal solution. Based on the greedy algorithm, a distributed MAC protocol was developed to conduct channel-width adaptation for all links in the WMN. Simulation results showed that the new MAC protocol outperformed MAC protocols with traditional channel-width adaptation. The channel-width adaptation mechanism studied in this paper assumes that the traffic demand on each link is given. In practice, traffic demand of a link is closely related to MAC/routing cross-layer design. How to consider channel-width adaptation under the framework of MAC/routing cross-layer design is a key factor to further improve the network performance of WMNs, which is an interesting topic for future research.

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AQ2 = Semi-colon was changed to comma. Please check if appropriate.
AQ3 = The preceding statement is incomplete. Hence, it was combined with the subsequent sentence. Please check if appropriate.

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