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Traffic-Demand-Aware Collision-Free Channel Assignment for Multi-Channel Multi-Radio Wireless Mesh Networks

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ABSTRACT In multi-channel multi-radio wireless mesh networks (MCMR WMNs), assigning each radio with an appropriate channel to maximize the performance is a challenging problem. In this optimization, the primal concern lays on how to mitigate effects of interference to avoid performance degradation. However, collision-freedom for a given traffic demand under the limitation of precious channel resources has not been achieved yet. In this paper, we present a collision-free joint channel assignment and routing scheme called TACCA (Traffic-demand-Aware Collision-free Channel Assignment) for MCMR WMNs. To reduce the required number of channels, TACCA incorporates a property of CSMA (Carrier Sense Multiple Access), i.e., it adopts CSMA-aware interference model and a CSMA-aware shared link capacity model. We formulate a mixed integer linear programming (MILP) to optimize the network utility and enhance the practical usefulness under the given traffic demands. The evaluation results with a MILP solver show that TACCA achieves collision-freedom in both grid and random topology networks with 3-5 orthogonal channels, and exhibits good network utilization performance. In addition, the network simulation results show that TACCA achieves mostly collision-free communications under up-to-date PHY and MAC models, and presents excellent communication performance.

INDEX TERMS WMNs, channel assignment, routing, collision-free, MILP.

I. INTRODUCTION

Wireless mesh network (WMN) is a communications network made up of radio nodes organized in a mesh topology. It is emerging as a promising technology for low-cost ubiquitous broadband Internet access via reduced dependency on the wired infrastructure [1], [2]. With the development of advanced radio technologies, multi-channel multi-radio (MCMR) technology can greatly enhance network performance in WMNs [3]–[7]. In MCMR WMNs architecture, each router is equipped with multiple radios, and each radio can be operated on one of the several distinct channels. Compared with single-channel and single-radio case, MCMR settings significantly increase network capacity, provide flexible connectivity, and reduce interference among neighboring links. Commodity IEEE802.11 devices are preferably used in MCMR WMNs due to less expense and easier deployment. However, given the limitation on the number of available network interface cards (NICs) on each mesh router, and the limitation of available orthogonal channels (e.g., the IEEE802.11 2.4GHz bands provides 3 orthogonal frequency channels), many links are forced to operate on the same channels, resulting in significant interference among transmissions. To assign each radio on each node with an appropriate channel to maximize network performance is a great challenge. Here, note that, routing configuration combined with channel assignment potentially reduces collisions. Moreover, it also contributes to the total network load balancing and controls. Therefore, joint channel assignment and routing promisingly lead to efficient configuration. However, in the current state of the art, there is no joint channel assignment and routing scheme that achieves collision-freedom with 3-5 channels. Our goal in this paper is to design a highly optimized joint channel assignment and routing scheme which achieves practical WMN with IEEE802.11.

Typically, channel assignment to minimize interference is done based on the model called conflict graph.

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Marina *et al.* [8] proposed the Connected Low Interference Channel Assignment (CLICA) algorithm for MCMR WMNs, which assigns channels to radio interfaces to minimize interference under conflict graph. Since the channel assignment problem is NP-hard, the authors proposed a heuristic algorithm to minimize the number of interference link pairs. However, collision-free channel assignment with 3-5 orthogonal channels has not been achieved.

Yoshihiro *et al.* [9] proposed the first collision-free static channel assignment CASCA (CSMA-Aware Static Channel Assignment) for MCMR WMNs within 3-5 orthogonal channels. CASCA introduces a CSMA-aware interference model which allows two links located within the carrier-sense range to share the same channel, whereas making two links that invoke hidden-terminal problem use different channels. To eliminate harmful effect of hidden terminal problem, CASCA partially introduces routing function, i.e., excluding a part of links from a set of links that forward packets, while simultaneously guaranteeing feasible paths for any pair of source-destination nodes. However, CASCA does not treat full-routing function so that it lacks flexibility in terms of traffic engineering, meaning that it can not cope with variation of traffic patterns, and it easily leads overload of some links under variation of input traffic demands.

In this work, we propose a new joint static channel allocation and routing method TACCA (Traffic-demand-Aware Collision-free Channel Assignment) that achieves collision-free channel assignment with 3-5 orthogonal channels while considering traffic demand and traffic engineering. Because of the NP-hardness of the problem [10], CASCA formulates the problem as a PMAX-SAT (Partial MAXimum SATisfiability) problem. However, PMAX-SAT handles 0/1 values and can not handle real values. Therefore, to treat the traffic demands, we mathematically formulate the problem as a MILP (mixed-integer linear optimization problem) and incorporate the link capacity, interference, the number of available radios, and channels, etc. In our study, we make the following set of contributions:

1) We introduce a traffic demand matrix into CASCA and formulate a joint channel assignment and routing problem within MILP framework. Note that the traffic demand matrix is defined statically although the demand dynamically changes with time. In practice, we can assume that the dynamism of the demand is sufficiently small and so we can define the traffic demand matrix that comprehend the dynamics based on some measurement or estimation of the real traffic.

2) We newly introduce a 'CSMA-aware' shared link capacity model to leverage the property of CSMA into link capacity computation and traffic engineering. Capacity modeling in relation with channel assignment is essential for routing to optimize the network performance. In the CSMA-aware interference model, links within the carrier-sensing range may be assigned with the same channel. Due to the characteristics of CSMA, all of those links within the carrier-sensing range share the link capacity.

3) To the best of our knowledge, our method TACCA is the first joint channel allocation and routing scheme which achieves collision-free transmission with small number of channels in the literature. With the CSMA-aware interference and shared link capacity models introduced, we achieved a traffic-demand aware collision-free channel assignment that optimizes MCMR WMNs under given traffic demands. Unlike CASCA that does not consider traffic demands, TACCA consistently selects both routing paths that satisfies the link capacity constraint, and channels that consistently avoid collisions. Same as CASCA and TiMesh, TACCA is able to work with commodity 802.11 hardware without requiring any MAC modifications or tight synchronization.

The rest of this paper is organized as follows. We present related work in Section II. We describe the system model, interference model, shared link capacity model, and some assumptions in Section III. We formulate the problem in Section IV. Performance evaluations are given in Section V. Conclusions are given in Section VI.

II. RELATED WORK

Channel assignment algorithms aim to assign channels to the radio interfaces with the objective of minimizing overall interference over wireless links, and maximizing communication performance. There are tremendous amount of studies on channel assignment in MCMR WMNs, which have been reported as surveys [11]–[17]. In the literature, the channel assignment can be formulated either as an independent problem that considers interference among links (e.g., [8]), or as joint problems combined with other constraints. The combined design generally has higher performance since various additional parameters are jointly considered in optimization. For instance, there are joint routing and link scheduling [18]–[20], joint power control [21], joint QoS multicast routing [22], joint gateway selection [23], joint power control and routing [24], and joint partially overlapped channel assignment [25], [26], etc. In this study we focus on combined channel assignment and routing because routing is the most effective joint factor to reduce collisions among links and improve performance of networks.

Joint channel assignment and routing schemes have been in progress for decades. Routing configuration is effective to reduce interference among links because it can make a part of links inactive and arrange logically sparse networks. In the formulation of optimization problems, several physical interference models have been considered such as single/double disk models [27], SINR model [28], and k-hop model [29], etc. Those models basically determine the range of interference, and two links within the range of each other collide if they communicate simultaneously. To avoid collision, those two links must use orthogonal channels. Hence, it is naturally easier to reduce collision in sparser networks. One typical use case of channel assignment is WMNs with commodity 802.11 interfaces, where nodes have multiple NICs to which channels are assigned in coordination with routing configurations. Since the number of available orthogonal channels in 802.11 is small, to eliminate collisions under smaller number of channels is a key challenge. Also, as the joint channel assignment and routing problem has been proved to be NP-hard [10], exploring efficient algorithms to find optimal solutions is another important challenge.

As a study tackling the challenges, Marina *et al.* [8] formulate a channel assignment problem based on traditional conflict graphs under protocol (i.e., single-disk) interference model, and provided a greedy algorithm. The result shows that heavy collisions remain with as many as 3-5 orthogonal channels. Raniwala *et al.* [30] proposed a centralized joint channel assignment and routing algorithm under double-disk interference model, and designed a heuristic algorithm to solve it. Although they incorporate joint routing scheme, their method still does not perform with 3-5 orthogonal channels. Lin *et al.* [31] proposed to apply genetic algorithm for the joint channel assignment and routing problem under protocol interference model. Although their method achieved better optimality than conventional optimization methods, collision freedom is not achieved with 3-5 channels. Avallone *et al.* [32] formulates a layer-2.5 forwarding scheme considering flow rate. They achieved a collision-free channel assignment under the assumption that links in a collision domain can share capacity within the sum of flow rates. However, to realize this without collision, some time-slot based scheduling under layer-2.5 forwarding is required, and MCMR WMNs with commodity 802.11 NICs do not support it. As above, collision freedom in MCMR WMNs with small number of channels is still a challenging problem.

Recently, a significant progress is brought in CASCA [9], which introduces a new CSMA-aware interference model. The CSMA-aware model allows two links located within the carrier-sense range to use the same channel, whereas making two links that invoke hidden-terminal problem use different channels. Simultaneously, CASCA allows to use longer paths than the shortest paths by k-hops in order to reduce collisions. This achieved collision-free channel assignment with 3-5 orthogonal channels in both grid and random scenarios. However, since they neither treat traffic demands nor provide full routing function, CASCA lacks flexibility in terms of practical efficacy. In this paper, we extend CASCA to support traffic demands and traffic engineering function to suffice practical requirements. To the best of our knowledge, our scheme TACCA is the first one that achieves collision freedom with 3-5 orthogonal channels in 802.11-based MCMR WMNs with traffic-demand support.

Finally, we would introduce TiMesh [33] and its directed-antenna extension [34], whose formulations are relatively close to our study in that they made a MILP-based formulation of joint channel assignment and routing problems with the constraint of forwarding paths length. The main difference is in the interference part. TiMesh aims at avoiding collisions using RTS/CTS handshakes so that links in a collision domain shares the capacity. However, RTS/CTS not only reduces performance due to the exposed terminal problem [35], but also does not work well in real environment due to interference of RTS/CTS frames. Through the simulation results, we later show that the introduced CSMA-aware interference model significantly reduces collisions compared to RTS/CTS schemes.

III. SYSTEM MODEL

In this section, we introduce our network model, CSMA-aware interference model, and shared link capacity model, which specifies the key characteristics our scheme TACCA.

A. NETWORK MODEL AND ASSUMPTIONS

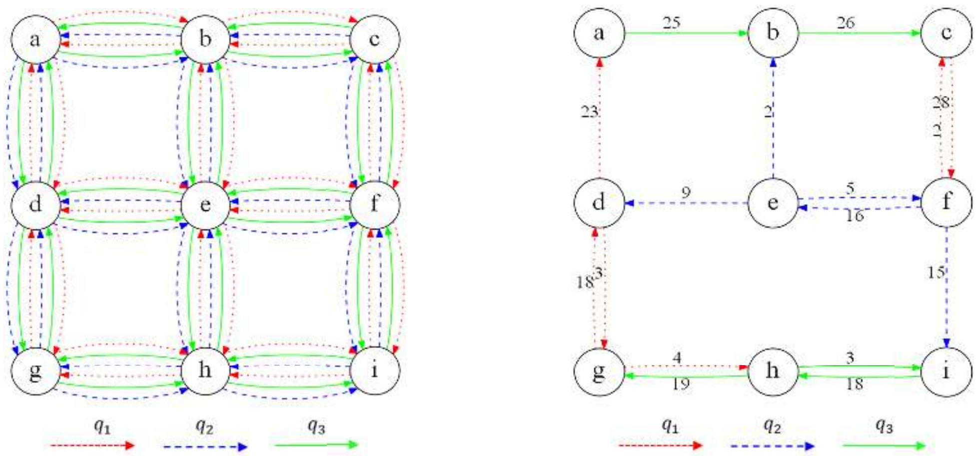
We model a MCMR network as a set of stationary nodes V connected by a set of directed links E. Then, digraph $G = (V, E)$ represents a network. Each node in V is equipped with multiple classic NICs built on IEEE802.11 technology, and each NIC operates on frequency channel. A link $\ell \in E$ that goes from node u to node v using channel $q \in Q$ is written as $\ell = (u, v, q)$, where Q is a set of orthogonal channels and $|Q|$ represents the number of the channels. Subsequently, we sometimes use the term (u, v, q) in place of link ℓ, where u and v are the terminal nodes of link ℓ. As described, $|Q|$ independent orthogonal channels are available for communications between every pair of nearby nodes u and v in V. Fig.1(a) illustrates the model network G in case of $|Q| = 3$, in which $2|Q|$ links are defined between neighboring nodes.

In addition, we are given a traffic demand matrix D, which represents the amount of traffic demand from node s to d for each pair $(s, d) \in V \times V$. The demand from s to d is written as $D(s, d)$. In order to represent the amount of traffic each link can afford, we assume each link has capacity C.

To introduce the collision-free and capacity constraint, we give additional definitions in the following sections.

B. CSMA-AWARE INTERFERENCE MODEL

To achieve collision-free transmission on the commodity 802.11 hardware, accurate interference model is very important. In this paper, we use the CSMA-aware interference model introduced in CASCA [9]. The CSMA-aware interference model is built on top of the single disk model, in which both the communication range and the interference range are the same, and is denoted by R. Therefore, given the 2D coordination of nodes in V, link $(u, v, q) \in E$ exists if the distance between nodes u and v is smaller than R, and both u and v have a NIC assigned with channel q. As is known, CSMA is a MAC protocol in which a node verifies the absence of other traffic before transmitting on a shared transmission medium. If a carrier is sensed, the node waits for the on-going transmission to end before initiating its own transmission. Basically in CSMA, multiple nodes would send and receive frames in turn on the same medium without collision unless hidden terminals exist. Therefore, in this study, we assume that the collision between links within carrier-sensing range are avoided due to CSMA, and regard that the two directed links interfere with each other only if they are located in the hidden-terminal position.



(a) Network Model (b) Optimization Result

FIGURE 1. One network model and an optimization result.

Let $\ell_1 = (u_1, v_1, q_1)$ and $\ell_2 = (u_2, v_2, q_2)$ be a pair of two links in E. Then, transmission on ℓ_1 prevents ℓ_2 due to collision of the hidden terminal effect if the following conditions are met.

Case 1: Collision of two Data frame.

(1) $q_1 = q_2$,

(2) $(u_1, u_2, q_1) \notin E$,

(3) $(u_1, v_2, q_1) \in E$.

Case 2: Collision of Data and Ack frame.

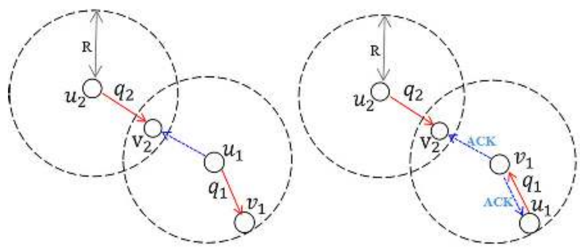
(1) $q_1 = q_2$,

(2) $(u_1, v_2, q_1) \notin E$,

(3) $(v_1, v_2, q_1) \in E$.

Case 1 defines the conditions where the transmission of data frame on ℓ_1 interferes the reception of data frames on ℓ_2. See Fig.2(a). Node v_2 is within the transmission range of both nodes u_1 and u_2, but nodes u_1 and u_2 are without the transmission range of each other, which results in collision because nodes u_1 and u_2 may simultaneously transmit frames to node v_1 and v_2, respectively, and they collide at v_2. Note that nodes v_1 and v_2 may be the same node. We regard such links ℓ_1 and ℓ_2 as an interference link pair, e.g., in Fig.1(a), link (a, b, q_1) and (c, b, q_1), as well as link (a, b, q_1) and (c, f, q_1) are interference link pairs, respectively.

Fig.2(b) illustrates the case 2 where the transmission of ACK frames on ℓ_1 interferes the reception of data frames on ℓ_2. As we know, CSMA attempts to assure frame delivery by using explicit acknowledgment (ACK), which means an ACK frame is sent by the receiving node to confirm that the data frame arrived intact. This ACK frame may cause collision. See Fig.2(b). Node u_1 and u_2 can not sense each other. So, when they simultaneously use the same channel to deliver frame to node v_1 and v_2, respectively, the ACK frame from node v_1 and the data frame from node u_2 may collide at node v_2. Also in this case, we regard such links ℓ_1 and ℓ_2 as an interference link pair. In the example in Fig.1(a), a pair of link (a, b, q_1) and (f, c, q_1) is an interference link pair in Case 2.



(a) Collision of two Data frames (b) Collision of Data and Ack frames

FIGURE 2. Two cases of interference.

We suppose interference is asymmetric: a transmission on link $\ell_1 \in E$ prevents communication of $\ell_2 \in E$ under this interference model. In this case, we regard that ℓ_1 interferes ℓ_2 and write $\ell_1 \rightarrow \ell_2$. Accordingly, we define a set of interference link pairs as follow,

$$I_G = \{(\ell_1, \ell_2) | \ell_1, \ell_2 \in E, \ell_1 \rightarrow \ell_2\}. \quad (1)$$

I_G is computed from the given network topology. Under the interference model given above, we compute a collision-free joint channel assignment and routing. Note that, in the CSMA-aware interference model, collisions due to neither simultaneous backoff expiration nor due to simultaneous transmission of two ACK frames are ignored because of low occurring probability. If we obtain the collision-free channel assignment and routing under this interference model, collision probability in real WMNs would be expected to be in sufficiently low level.

C. SHARED LINK CAPACITY MODEL

In wireless networks, a frequency channel is shared by nodes within the carrier-sense range, and so the links around the nodes share a capacity. See Fig.1(b), for an example of optimization results. Links (e, b, q_2), (e, d, q_2), (e, f, q_2), (f, e, q_2), and (f, i, q_2) share the capacity since transmitting nodes e and f are within their carrier sense range with each other. Therefore, a wireless link in a MCMR WMN does not have dedicated bandwidth since neighboring node's transmissions contends for the same bandwidth. To ensure high network performance, the amount of traffic loads through all these shared capacity links should not exceed the capacity C. As aforementioned, links (e, b, q_2), (e, d, q_2), (e, f, q_2), (f, e, q_2), and (f, i, q_2) in Fig.1(b) are shared capacity links.

We define the set of shared capacity links in terms of node v and a frequency channel q as follows,

$$S_v^q = \{(v,u,q)|(v,u,q) \in E\} \cup \{(u,v,q)|(u,v,q) \in E\} \cup\{(u,a,q)|(u,v,q) \in E, (u,a,q) \in E, a \neq v\}. \quad (2)$$

See Fig.3, where $u \in V$ is a node within the sensing range of node $v \in V$, and $a \in V$ is excluded from the sensing range of v while included in the sensing range of u. Then, if the links (v, u, q), (u, v, q), (u, a, q) are assigned with the same channel q, they will share the link capacity C under CSMA. Note that S_v^q is defined for each node $v \in V$ because all nodes in v's collision domain do not always share capacity (Imagine that node u' such that $(v, u', q) \in E$ exists in Fig.3. Then, u' is in a carrier sense range of v, but may not in that of u. Therefore, u and u' may not share capacity). Note also that links such as (a, u, q) is not included in S_v^q because they collides with (v, u, q) etc. Due to hidden terminal effect, and the interference constraint described in following Section IV does not allow those collision links to be active simultaneously.

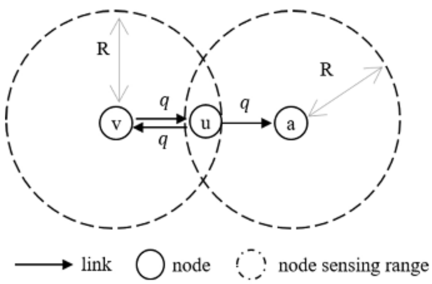


FIGURE 3. Shared capacity schematic diagram.

IV. PROBLEM FORMULATION

In this section, we formulate a joint channel allocation and routing problem in MILP, and show the whole formulation.

We first provide basic variable definitions. Due to the structure of MCMR networks, we assume each node v is equipped with N_v NICs and each NIC on a node operates on a distinct frequency channel in Q. Two nodes must be assigned with same channel to communicate with each other. Therefore, if a link $\ell = (u, v, q)$ is used to transmit frames, we call it is active, channel q must be assigned to a NIC of both u and v. We define a variable $F_v^q \in \{0, 1\}$ indicating whether node v is assigned with frequency channel q or not, i.e., $F_v^q = 1$ if there is a NIC on node v assigned with frequency channel q, and $F_v^q = 0$ otherwise.

As previously described, we make a channel assignment for a given traffic demand D. Therefore, for each non-zero demand $D(s, d)$, we set a path to forward the traffic from s to d. With each pair (s, d) and each link ℓ, we associate a variable $P_\ell^{(s,d)} \in \{0, 1\}$ that indicates whether the traffic flow for demand (s, d) goes through link ℓ or not, i.e., $P_\ell^{(s,d)} = 1$ if the routing path from s to d includes link ℓ, and $P_\ell^{(s,d)} = 0$ otherwise.

If link ℓ is included in some routing path from s to d, i.e., $P_\ell^{(s,d)} = 1$ for at least one pair of s and d, we call link ℓ is active as it is used for packet transmission. A variable $A_\ell \in \{0, 1\}$ is defined, where $A_\ell = 1$ indicates link ℓ is active and $A_\ell = 0$ is inactive.

Our optimization objective is to make the maximum link utilization in the network minimized. The link utilization is the ratio of traffic amount over the link capacity C, i.e., the utilization of link $\ell \in E$ is expressed as $\sum_{(s,d)\in V\times V} D(s,d)P_\ell^{(s,d)}/C$. Thus, we define a variable U_{max} ($0 \leq U_{max} \leq 1$) represents the maximum link utilization among all links. When the maximum of link utilization is minimized, the percentage of the residual bandwidth on links, i.e., unused bandwidth, is maximized. Therefore, the growth in traffic in the future is more likely to be accommodated and can be accepted without requiring the re-arrangement of assigned paths. To summarize the definition above all, we give a table of the notations in Table 1.

TABLE 1. Notations for TACCA.

Symbol	Description
V	A set of stationary nodes (routers)
E	A set of directed links
G	A directed network
C	Link capacity (common with all links)
Q	A set of orthogonal channels
D	A traffic demand matrix
$D(s,d)$	A traffic demand from s to d
$\ell/(u,v,q)$	A link
I_G	A set of interference link pairs
S_v^q	A set of shared capacity links
F_v^q	Binary variable indicating node v is assigned channel with q or not
$P_\ell^{(s,d)}$	Binary variable indicating whether path of $D(s,d)$ includes link ℓ or not
A_ℓ	Binary variable indicating link ℓ is active or not
U_{max}	Real variable indicating maximum link utilization

With those notations, given the network topology and the expected traffic demand matrix, the general routing and channel assignment problem can be formulated in MILP framework as follows,

$$\min \quad U_{max} \quad (3)$$

$$\textit{Subject to} \sum_{q\in Q} F_v^q \leq N_v, \qquad \forall\ v \in V, \quad (4)$$

$$F_v^q \leq \sum_{(v,u,q)\in E} A_{(v,u,q)} + \sum_{(u,v,q)\in E} A_{(u,v,q)}, \quad \forall\ q \in Q,\ \forall\ v \in V, \quad (5)$$

$$A_{(u,v,q)} \le F_v^q, \quad A_{(u,v,q)} \le F_u^q, \quad \forall \ (u,v,q) \in E, \tag{6}$$

$$\sum_{(u,v,q)\in E} P_{(u,v,q)}^{(s,d)} D(s,d) - \sum_{(v,w,q)\in E} P_{(v,w,q)}^{(s,d)} D(s,d) = \begin{cases} -D(s,d), \text{if } v = s, \\ D(s,d), \text{if } v = d, \\ 0, \text{otherwise}, \end{cases} \quad \forall (s,d) \in V \times V, \tag{7}$$

$$\sum_{(s,d)\in V\times V} P_\ell^{(s,d)} \le MA_\ell, \quad \forall \ \ell \in E, \tag{8}$$

$$\sum_{(s,d)\in V\times V} P_\ell^{(s,d)} \ge A_\ell, \quad \forall \ \ell \in E, \tag{9}$$

$$\sum_{(s,d)\in V\times V, \ell\in S_v^q} D(s,d) P_\ell^{(s,d)} \le U_{max} C + (1 - F_v^q) W, \quad \forall \ v \in V, \ \forall \ q \in Q, \tag{10}$$

$$A_{\ell_1} + A_{\ell_2} \le 1, \quad \forall \ (\ell_1, \ell_2) \in I_G, \tag{11}$$

$$\sum_{\ell\in E} P_\ell^{(s,d)} \le \delta_{s\to d} + k, \quad \forall \ (s,d) \in V \times V, \tag{12}$$

where

$$0 \le U_{max} \le 1, \tag{13}$$

$$F_v^q \in \{0,1\}, \quad \forall \ q \in Q, \quad \forall \ v \in V, \tag{14}$$

$$A_\ell \in \{0,1\}, \quad \forall \ \ell \in E, \tag{15}$$

$$P_\ell^{(s,d)} \in \{0,1\}, \quad \forall \ (s,d) \in V \times V, \quad \forall \ \ell \in E. \tag{16}$$

Formula (3) is our objective function. We try to minimize the maximum of link utilization in all the network. Therefore, (3) makes traffic flows move from congested hot spots to less utilized parts of the network, and leaves more space for future traffic growth or fluctuation.

Constraint (4) denotes the relationship between NICs and channels. To decrease the interference, we allow to assign no channel for some NICs. Therefore, the number of distinct frequency channels q allocated to one node must be less or equal to the number of NICs on each node N_v.

Constraint (5) and (6) denote the relationship between links and channels. For each node v, $(v,u,q) \in E$ denotes the output links of node v, and $(u,v,q) \in E$ denotes the input links. Node u is the other terminal node of links (v,u,q) and (u,v,q). See Fig.1(a), network topology is defined as a multiple graph in which neighboring two nodes may have multiple links corresponding to each channel in Q. Therefore, as indicates in (5), if a NIC on node v is assigned with channel q, i.e., $F_v^q = 1$, then $\sum_{(v,u,q)\in E} A_{(v,u,q)} + \sum_{(u,v,q)\in E} A_{(u,v,q)} \ge 1$, this means at least one connecting link (no matter output or input link) must be activate. Conversely, as indicated by (6) if none of the NICs on node v is assigned with channel q, i.e., $F_v^q = 0$ and $F_u^q = 0$, then $A_{(u,v,q)} = 0$, it means none of the connecting links is active.

Constraint (7) denotes the traffic flow conservation. Traffic flows in the network must meet the conservation conditions. In (7), $P_{(u,v,q)}^{(s,d)}$ and $P_{(v,w,q)}^{(s,d)}$ denote whether the route of traffic demand (s,d) goes through the input link (u,v,q) and output link (v,w,q) of v, respectively. For each traffic demand pair (s,d), we refer to s and d as the source and destination nodes of the demand. From the viewpoint of flow conservation, the total volume of flows sent by s must be equal to that received by d. Also, the total input and output volume of flows on every intermediate node must be equal. If node v is the source node, i.e., $v = s$, the value of (7) equals to $-D(s,d)$. If node v is the destination node, i.e., $v = d$, the value of (7) is equal to $D(s,d)$. Otherwise, the node is intermediate node, and the value of (7) equals to 0. This constraint not only ensures that the traffic flow is properly routed from s to d, but also ensures that each demand is satisfied with a single explicit route.

Constraint (8) and (9) denote the relationship between traffic flows and links. Activated link must be traffic flows whose route go through it. Conversely, inactivated link has no traffic flow going through. In (8), M is a constant whose value is large enough. When at least one traffic flow goes through link ℓ, i.e., $\sum_{(s,d)\in V\times V} P_\ell^{(s,d)} \ge 1$, then the link ℓ must be activated, i.e., $A_\ell = 1$, we get $1 \le \sum_{(s,d)\in V\times V} P_\ell^{(s,d)} \le M$. Formula (9) means that if there is no traffic flow through link ℓ, the link ℓ must be inactivated, i.e., $A_\ell = 0$, then $\sum_{(s,d)\in V\times V} P_\ell^{(s,d)} = 0$. Both formula (8) and (9) keep the relationship between traffic flows and link activeness.

Constraint (10) is the constraint on link capacity. Recall that in CSMA-based wireless networks, links within the carrier-sensing range are regarded to share the link capacity as described (2). Therefore, the total traffic loads within one node's transmission range can not exceed the link capacity C. In (10), W is a constant whose value is large enough. If channel q is assigned to node v, then $F_v^q = 1$, and (10) is valid, i.e., we get $\sum_{(s,d)\in V\times V, \ell\in S_v^q} D(s,d) P_\ell^{(s,d)} \le C$, which ensures the total traffic loads of the all shared capacity links of node v do not exceed the link capacity C. Otherwise, if channel q is not assigned to node v, then we get $\sum_{(s,d)\in V\times V, \ell\in S_a^q} D(s,d) P_\ell^{(s,d)} \le C + W$, meaning that there are no capacity constraints on these links. Note that, in (10), we replace C with $U_{max} C$ where U_{max} is the maximum utility in the whole network. This is because we aim at optimizing the maximum utility to provide the load balancing function.

Constraint (11) is the interference constraint which ensures that interfering links are not assigned with the same channel. Recall to (1), links $(\ell_1, \ell_2) \in I_G$ can not be activated simultaneously, i.e., if $A_{\ell_1} = 1$, then there must be $A_{\ell_2} = 0$, and vice versa.

Constraint (12) is on path length. In our scheme, we allow each of the traffic flows from s to d to be detoured. $\delta_{s\to d}$ indicates the minimum hop count to reach d from s, i.e., the shortest-path length from s to d in G. $k \ge 0$ is a path stretch in integer, then $\delta_{s\to d} + k$ means that length of every path is limited by the shortest path length plus k. Length of all paths are controlled by adjusting the value of k.

Constraints (13), (14), (15), and (16) define the domains of variables described previously.

With above formulation, our problem assigns a single path for every non-zero traffic demand pair (s, d) in D, where both the link capacity constraint and the collision-free constraint are fulfilled, and the link utilization is minimized. Note that our idea to utilize the property of CSMA is included in constraint (10) and (11) where CSMA-based link-capacity sharing model is applied in (10) and CSMA-aware interference model is used to compute I_G in (11). See Fig.1(b) again, which is an example of optimization results under the traffic demand matrix D that offers flows from every node to all the other nodes. In this schedule, we assume $D(s, d) = 1$ for all pairs of s and d, link capacity is $C = 60$ (unit), and $N_v = 2$ for every $v \in V$. We also assume that each radio reaches and interferes the neighbor nodes in vertical and horizontal direction. We see that each node is assigned with no more than two channels, e.g., except node e being assigned with 1 channel, all other nodes are assigned with 2 distinct channels, respectively. The numbers given on each link indicates the amount of traffic loads through it, e.g., the route from d to e is $d \rightarrow a \rightarrow b \rightarrow c \rightarrow f \rightarrow e$, and the number 16 on link (e, f, q_2) means that there are 16 flows like this that goes through this link. As we will describe in Section III-C, the sum of the traffic flow rates going over each link does not exceed the link capacity $C = 60$, and $U_{max} = (25+26)/60 = 0.85$ regarding the links (a, b) and (b, c). It is clear that there is no collision among links that have flows travelling on them.

V. EVALUATION

We evaluate the performance of our method TACCA with two different network topologies, i.e., a grid topology and a random topology. We evaluated both the optimization performance through a MILP solver, and the communication performance through simulation. In the former part, we computed the channel assignments with various parameter settings to show the property of the formulated problem. As for the latter, we made a traffic simulation using an up-to-date network simulator. We describe the detail in the following sections.

A. OPTIMIZATION PERFORMANCE EVALUATION

In this evaluation, we see the performance of TACCA under various values of the parameters such as offered traffic load, the number of channels, and path stretch k. One of the important viewpoints is whether collision-free channel assignment with 3-5 orthogonal channels is possible or not with the CSMA-aware interference model. Another concern is the load-balancing performance against traffic demands with various values of path stretch k. Both are examined in two scenarios with grid and random topologies.

1) METHOD

We solved our MILP problem with MATLAB R2019b with the optimization toolbox [36], which was executed on a computer with Intel (R) Xeon (R) CPU E3-1280 (3.70 GHz), 64 GB memory. As typical scenarios in WMNs, we suppose two different types of network topologies, i.e., grid and random layout of wireless nodes. As for grid topology, we designed a 5×5 square grid with 400 meters interval in both horizontal and vertical directions. On the other hand, as a random topology, we located 30 nodes with random coordination in a $1,200 \times 1,200$ meters square field. We assume that each node has 2 NICs, and the communication range is 530 meters that corresponds to 20 dBm Txpower. Each NIC operates IEEE 802.11g with 6 Mbps communication speed so that the link capacity C is also 6 Mbps.

As the traffic demand given, we generate flows intending highly collided traffic that covers a certain area of field; We generate 12 bi-directional Constant Bit Rate (CBR) flows in the grid topology, and in the random topology, we generate 10 CBR flows with randomly selected source and destination nodes. In both scenarios, we test variation of flow volume to see the capacity of the networks. We show the grid topology and flows in Fig. 4, and the random topology in Fig. 5.

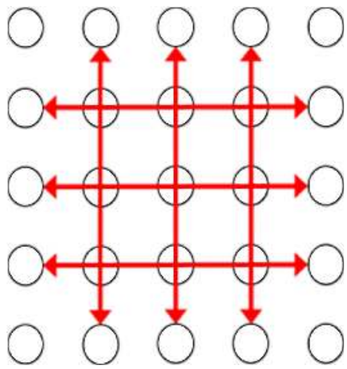


FIGURE 4. Traffic pattern (5 × 5 grid topology).

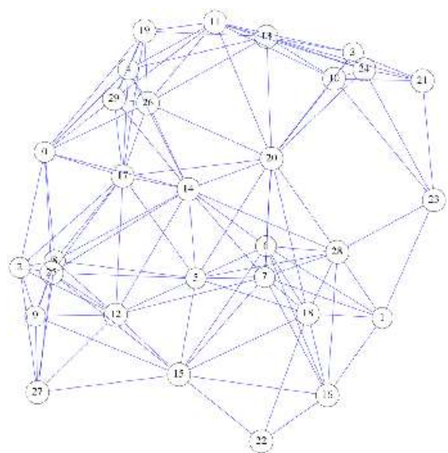
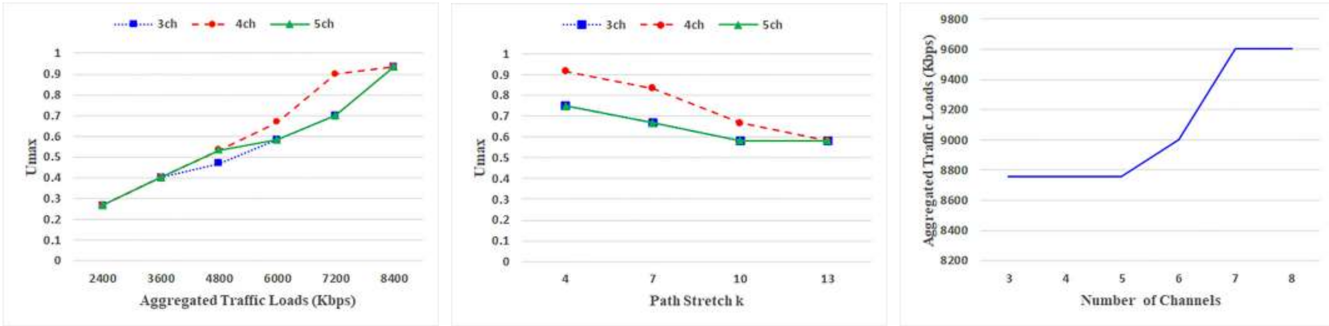
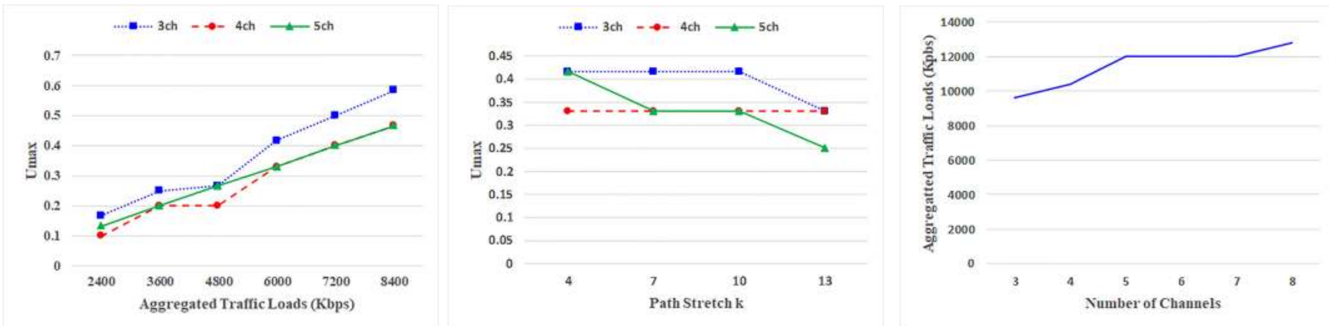


FIGURE 5. 30 nodes random topology.

Note that the MATLAB computation would take for very long time because of the NP-hardness of the problem. Thus, in our evaluation, we set the maximum execution time limited to 7,200 seconds. Namely, we obtain the best solution found within the time limitation. The whole configuration described above is summarized in Table 2.



(a) Maximum Link Utilization with Traffic Load (Grid Topology)
(b) Maximum Link Utilization with Path Stretch k (Grid Topology)
(c) Supportable Traffic Loads (Grid Topology)



(d) Maximum Link Utilization with Traffic Load (Random Topology)
(e) Maximum Link Utilization with Path Stretch k (Random Topology)
(f) Supportable Traffic Loads (Random Topology)

FIGURE 6. Results of optimization performance evaluation.

TABLE 2. Configuration in optimization evaluation.

Items	Values
Solver	Matlab2019b with the optimization toolbox
Number of Channels	≥ 3
Number of Interfaces	2 for each node
Link Capacity	6 Mbps
Communication Range	530 meters
Network Topology	Grid and Random
Number of Nodes	25 (Gird), 30 (Random)
Traffic Demands	12 CBR flows (Grid)
	10 CBR flows (Random)

2) RESULT

We begin with the results of the grid topology. Fig. 6(a) shows the relationship between the optimization function U_{max} and the offered traffic load in the demand matrix with path stretch $k = 10$. Note that the horizontal axis represents the aggregated traffic volume, i.e., the total offered load of 12 bi-directional flows. First, we found that the collision-free solution surely exists even when the number of channels is 3. Next, we see that the link utilization U_{max} gradually increases as the offered load increases. This means that the network utilization U_{max} is in proportion to the amount of offered load, which implies that traffic load is well balanced with $k = 10$. On the other hand, we do not see the effect of the number of channels with 3-5 channels; This point would be mentioned later in Fig. 6(c).

In Fig. 6(b), we show the effect of path stretch k with the maximum network link utility U_{max}. We see that U_{max} decreases as k increases. This again shows that the load balancing function works, and the effect increases as k increases. In Fig. 6(c), we show the result on supportable offered load with $k = 10$ under variation of the number of channels. The vertical axis represents the total offered load of the traffic demand so that the figure indicates the maximum volume of traffic demand that MATLAB could compute within the configured limited time. From the result, we see that the supportable traffic volume does not change with 3-5 channels as we have already seen in Fig. 6(a), whereas the supportable traffic volume rapidly increases with 6-8 channels. This means that the number of channels has a large effect on the network capacity, but unfortunately the effect is not seen with 3-5 channels in the grid scenario.

We show the results of the random topology in Figs. 6(d), (e), and (f). Those results present the similar trend as the grid topology. Namely, the effect of load balancing is seen in Fig. 6(d), the effect of path stretch k is seen in Fig. 6(e), and the effect of the number of channels is seen in Fig. 6(f). Note that the effect of the number of channels on the supportable traffic volume is seen even for 3-5 channels in the random scenario in Fig. 6(f).

As above, in the optimization evaluation, we confirmed the property of TACCA under parameter variations. TACCA computes a collision-free channel assignment combined with routing configuration with 3-5 channels, and its load balancing effect is clearly seen depending on k and the number of channels.

TABLE 3. Configuration in traffic simulation.

Items	Values
Simulator	Scenargie version 2.1
PHY and MAC Protocols	IEEE802.11g
Propagation Model	Two ray ground
Link Capacity	6 Mbps
Transmission Power	20 dBm
Number of Interfaces	2 for each node
Number of Channels	3
Communication Range	530 m
Network Topology	Grid and Random
Traffic Demands	12 CBR flows (Grid)
	10 CBR flows (Random)
Payload Size	1472 bytes
Number of Nodes	25 (Grid) and 30 (Random)
Simulation Time	5000 seconds

B. COMMUNICATION PERFORMANCE EVALUATION

1) METHOD

We made simulations using a commercial network simulator Scenargie version 2.1 [37], which implements up-to-date PHY and MAC models. Note that Scenargie adopts equivalent-level models with popular network simulators ns-3 and Qualnet, and the simulation performance have been verified through calibration among them. The simulation configuration is almost the same as optimization evaluation, as shown in Table 3. Each node is equipped with 2 NICs which operates IEEE802.11g in 6 Mbps speed with 20 dBm transmission power. We use the two-ray-ground model as the radio propagation model. We use the same topologies as the optimization evaluation; the 5×5 grid topology with 400 meters interval, and the random topology in a 1200×1200 meters square field. We generate 12 bi-directional CBR flows in the grid topology, and 10 flows with a random source and destination selection in the random topology.

We use a channel assignment and routing schedule obtained in the optimization evaluation. Specifically, we chose the schedule with 3 orthogonal channels, $k = 10$, and the offered traffic load is 500 Kbps per flow. As mentioned earlier, we are targeting on the mesh networks built with IEEE802.11 technologies. Generally, 2.4GHz band is regarded as more useful than 5GHz band for mesh infrastructure in many cases. Note that 3 is the minimum number of channels with which we got collision-free schedules, and also 3 is a practically useful number of channels since we can take only 3 orthogonal channels in 2.4 Ghz band in IEEE802.11, $k = 10$ is a value with good load balancing performance.

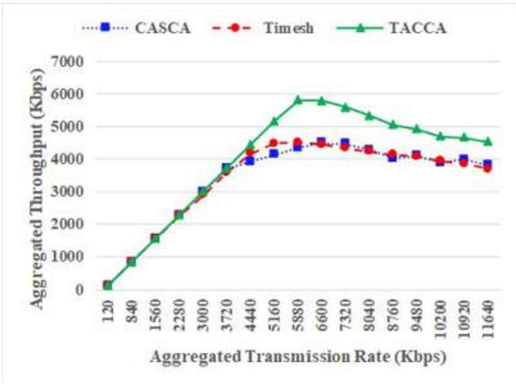
We compare the performance of TACCA with CASCA and TiMesh. Recall that there is a few schemes that achieves collision-free schedule with 3-5 channels in CSMA-based MCMR WMNs. Thus, most of the past schemes in the literature are not comparable in performance. Actually, as shown later, TACCA achieves almost 100% packet delivery unless the traffic volume exceeds the network capacity, and so the schemes with considerable collisions with 3 channels are not suitable to compare. Since CASCA achieves a collision-free schedule but does not consider traffic demands, we can see the performance gain of TACCA coming from considering traffic demands. Therefore, the CASCA schedule with the same parameters, i.e., 3 channels and $k = 10$ is used in the comparison. TiMesh has a close strategy to TACCA as it aims at minimizing network utility for a given traffic demand, and uses a path stretch parameter. However, it applies traditional RTS/CTS handshakes instead of interference models to cope with collisions among frames. Through comparison, we would see the performance of our CSMA-aware interference model compared with RTS/CTS handshakes.

We ran the simulator for 5000 seconds and measure the average of the communication performance with five repeated executions, and compare those three schemes in terms of throughput, packet delivery ratio, end-to-end delivery delay, and frame drop, which because collisions continue on a regular basis and so do the MAC layer retransmission with the final result effecting throughput, delivery, latency, and frame drop. Here, frame drop is included to show the state of collision and interference in the network. Since frame loss invokes frame retransmissions in MAC layer, it effects on the performance in throughput, delivery delay, and delivery ratio.

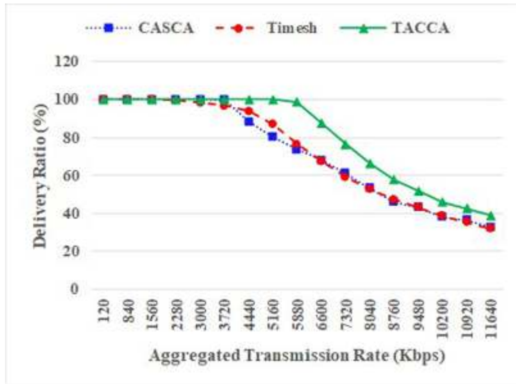
2) RESULTS

We show the results of the grid topology in Figs. 7(a), (b), (c), and (d). In Fig. 7(a), we show the aggregated throughput of the three schemes with the offered traffic volume as its horizontal axis. We see that all performs good when the offered load is low, but the performance of TiMesh and CASCA drop down with smaller offered load than TACCA. It was confirmed that CASCA met a bottleneck link, i.e., the link whose traffic load exceeded its capacity, with lower offered load than TACCA, proving that the load balancing function in TACCA well worked to enhance network capacity. In TiMesh, a considerable number of packets got stuck at source nodes. This is due to overhead of RTS/CTS handshake. Although TiMesh has the load-balancing function, the overhead of RTS/CTS due to exposed terminal problem extremely degrades the network capacity. As a result, TACCA outperforms the others in network capacity.

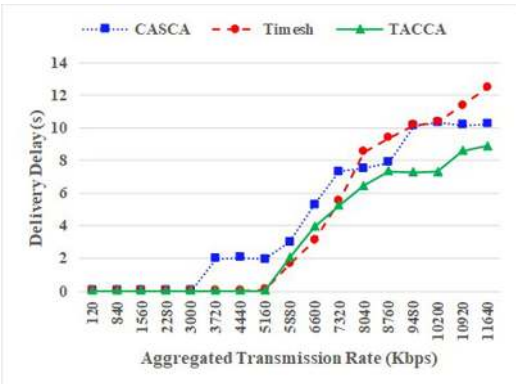
In Fig. 7(b), we show the packet delivery ratio with the offered traffic volume. Here, we see that TACCA keep almost 100% packet delivery unless the traffic volume reaches their network capacity, meaning that the collision-freedom property in the schedule lives in the simulation. In contrast, in TiMesh, delivery ratio gradually decreases as traffic volume increases even when the traffic volume is relatively low. We confirmed this is mainly caused by the collision of RTS/CTS frames due to hidden terminal problem. TiMesh still suffers from hidden terminal problem even under RTS/CTS mechanisms. We show the packet delivery delay in Fig. 7(c). We see the delivery delay rapidly increases when the network saturates (i.e., when the traffic load exceeds



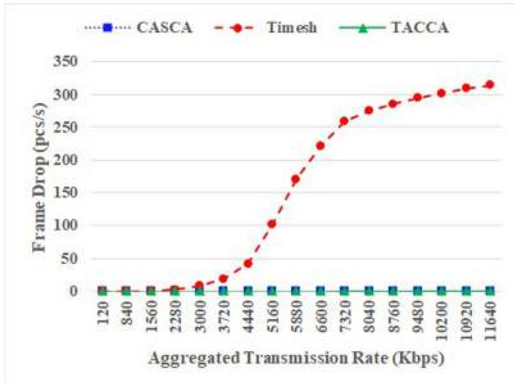
(a) Throughput (Grid Topology)



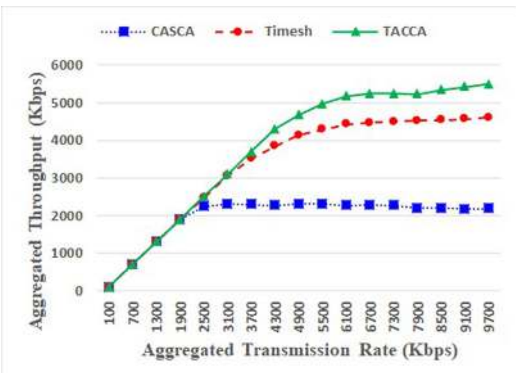
(b) Delivery Ratio (Grid Topology)



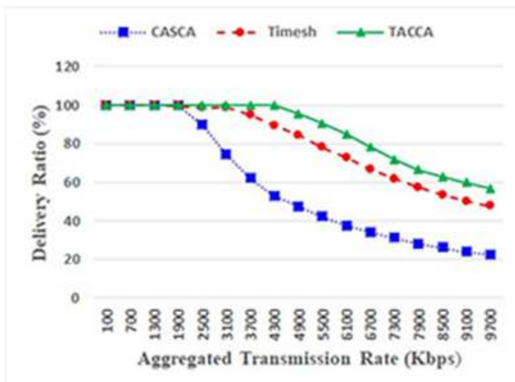
(c) Delivery Delay (Grid Topology)



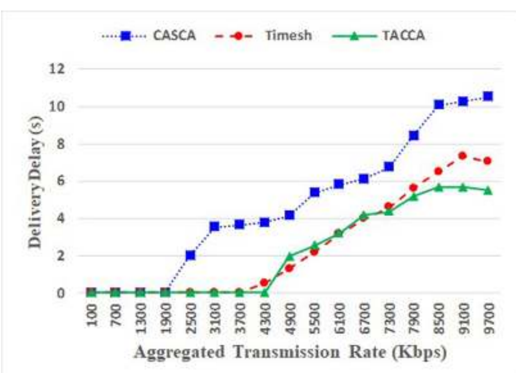
(d) Frame Drop (Grid Topology)



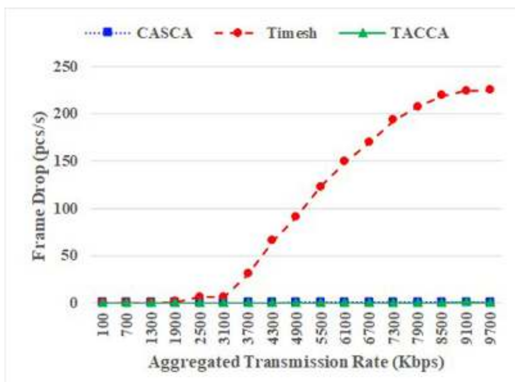
(e) Throughput (Random Topology)



(f) Delivery Ratio (Random Topology)



(g) Delivery Delay (Random Topology)



(h) Frame Drop (Random Topology)

FIGURE 7. Communication performance evaluation.

the capacity of some links) in all of CASCA, TiMesh, and TACCA.

Fig. 7(d) shows the status of frame loss in MAC layer due to collisions or interference. It is shown that, in TiMesh, the loss of frames increases as the volume of traffic increases. We observed a large number of RTS/CTS frames dropped because of exceeding the limit of retransmission counts, and most of them were due to collision of the hidden terminal problem. In contrast, in CASCA and TACCA, the number of dropped frames is very small; we observed only a few frame drops, which were due to interference or simultaneous backoff expiration, and they all were recovered by CSMA's frame retransmission.

In Figs. 7(e), (f), (g), and (h), we show the same set of results in the random topology scenario. Note that the result is the average of 4 different random topologies. Although the performance of CASCA and TACCA degrades compared with the grid scenario, the general trend is the same as the grid scenario. Namely, TACCA has the highest network capacity under the given traffic demand, and keep almost 100% packet delivery with higher offered load than CASCA and TiMesh. As above, we conclude that TACCA outperforms CASCA and TiMesh in both grid and random scenarios, and has an ability to keep collision-freedom with high offered load even if the number of available channels is as small as 3. Because of the collision freedom property with 3 channels, TACCA would naturally achieve collision freedom with more than 3 channels, and consequently outperform the others.

C. DISCUSSION

In theory, CASCA, TiMesh, and TACCA are all collision-free transmission schemes, which achieves 100% packet delivery without collision under their own interference model. However, in the simulation running with SINR interference model, we observed a certain level of collision caused by interference.

In TiMesh, except the loss due to queue overflow that occurs when traffic volume exceeds link capacity, the main cause of frame loss is the collision of RTS/CTS frames due to interference among hidden terminal nodes. This sort of frame loss increases as the volume of traffic increases, and is reflected on the decrease of delivery ratio seen in low-traffic-volume cases. In contrast, in CASCA and TACCA, we observed only a few frame drops, which were due to interference or simultaneous backoff expiration, and they all were recovered by CSMA's frame retransmission. As a result, CASCA and TACCA have almost no frame loss due to interference, shown as Figs. 7(d) and (h). This shows that the interference model in TACCA and CASCA well performed to reduce the interference among nodes.

The typical pattern of performance degradation in TACCA is seen when the distance between two nodes assigned with the same channel is slightly larger than the communication range R. See Fig. 5 again. A Node Pair 0 and 9 is the case, in which a link between them does not exist while radio of a node interferes the other. In this case, for instance, a transmission on link $(0, 26)$ would prevent successful transmission on link $(15, 9)$. In our simulation, we observed the case in each random topology although the frame drops due to this were all recovered by retransmission of frames. Here, we must notice that this case degrades the load balancing performance. If the radio of one of the node pair is sensed by the other, it introduces error in the capacity estimation of TACCA because the assumption in shared link capacity model is violated. This inconvenience in load balancing were also seen in our random topology simulations, which was the main cause of performance degradation of TACCA in random scenario compared with grid scenario.

VI. CONCLUSION

In MCMR WMNs, collision-free channel assignment has been one of the key challenges toward practical IEEE802.11-based WMNs. In this paper, by incorporating the CSMA-aware interference model introduced in CASCA, we proposed TACCA, which is a new joint channel assignment and routing scheme that achieves collision-freedom with 3-5 orthogonal channels, which also minimizes the network-wide utility under a given traffic demand matrix. Different from CASCA, we formulated the optimization problem as MILP to introduce a traffic engineering function under the CSMA-aware link capacity sharing model, which enables capacity management in MCMR WMNs under traffic demand. Through evaluation with the MATLAB MILP solver, we confirmed that TACCA achieves collision-freedom with 3 channels in both scenarios, and has good traffic engineering performance brought from the parameter called path stretch k. Results of traffic simulations show that the schedule computed by TACCA works without major collision under the up-to-date simulation models, and TACCA clearly outperforms the conventional schemes in them. To the best of our knowledge, TACCA is the first joint channel assignment and routing scheme that enables capacity management in MCMR WMNs under collision-freedom with 3-5 orthogonal channels. Note that collision-freedom is a key issue for the reliable capacity management. We believe that TACCA would provide an important contribution toward realizing practical IEEE802.11-based MCMR WMNs.

Several challenges remain for the future of MCMR WMNs. One of them is to apply improved interference models; Since TACCA's CSMA-aware interference model is based on single-disk model, the current schedule would not work efficiently with higher-speed links. Applying improved CAMA-aware interference models based on such as double-disk or SINR models would be important. On the other hand, exploring methods to coexist with other existing Wi-Fi APs and devices, or adapting to the dynamic transition of traffic demand would be other important future tasks.

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