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Link-speed Aware Scheduling for Slotted-CSMA Based Wireless Mesh Networks

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Abstract - We focus on Slotted-CSMA based architecture of wireless mesh networks (WMNs) and propose a scheduling algorithm to eliminate hidden terminal effects even with high-speed IEEE802.11 links. To take high-speed links and its physical properties into account, we introduces so called the double-disk interference model in computing the scheduling algorithm that eliminates hidden-terminal effects that severely degrades the network performance. Also, toward the automated computation of schedules, we propose to measure the interference range of the double-disk model by incorporating beacons in IEEE 802.11. Through evaluation, we confirmed that the proposed scheduling algorithm works well in WMNs with high-speed links.

Keywords: Wireless Mesh Networks

1 INTRODUCTION

Wireless Mesh Networks (WMNs) has been deeply studied in the literature as a high-speed wireless network infrastructure to cover a large geometric area with less economical cost [1]. Aiming at wide applications utilized by general users, commodity IEEE 802.11 devices are often used in WMNs. Taking advantages of CSMA MAC, we can share precious frequency resources with many devices, which enable us to build WMNs on the shared bands such as 2.4 and 5GHz. We currently have a standard IEEE.802.11s that realizes to form a mesh network over Wi-Fi APs.

However, unfortunately, WMNs have not been succeeded so far due to heavy interference between wireless nodes. Although IEEE802.11 utilizes CSMA to avoid collisions [2], the simple carrier-sensing-based mechanism suffers from so called the hidden-terminal effects, which heavily degrades the communication performance. The well-known RTS/CTS handshake is typically used to cope with this problem [3] as is included in IEEE802.11 standard. However, the effect of RTS/CTS is known to be limited due to several reasons such as probabilistic collisions in RTS/CTS handshake, excessive suppression of transmissions known as the exposed terminal problem [4], and the inconsistency effects caused by difference between transmission range and interference range [5]. Even recently, IEEE802.11-based wireless mesh networks suffers from heavy interference among nodes [6].

To minimize the effect of interference, several studies propose *routing metrics* that reflects on the quality of wireless links that dynamically transits with time [7]-[9]. By computing the shortest paths with respect of routing metrics, we can choose the best paths with small interference. For example, Couto et al., proposed ETX that represents the expected transmission count of data frames under IEEE802.11 [7]. Draves et al., proposed ETT that represents the expected transmission time to transmit frames [8]. However, the effect of those routing-metric-based optimization is marginal since considerable amount of interference remains and degrades significantly the performance.

Many schemes using multiple frequency channels have been proposed to improve communication speed in wireless mesh network. References [8] [10] proposed routing metrics to minimize interference in WMNs in which each node has multiple network interface cards (NICs). Marina et al. proposed a greedy algorithm that statically assigns frequency channels to NICs [11] in order to minimize the interference in WMNs. Mo et al. compared and evaluated multi-channel MAC protocols where a single network interface dynamically switches communication channels among multiple channels [12]. However, these multi-channel schemes do not substantially improve the communication performance due to difficulty in timing synchronization between senders and receivers, and also due to the small number of available orthogonal channels under Wi-Fi, i.e., 3 channels.

On the other hand, several hybrid MAC protocols that take advantages of both CSMA and TDMA have been proposed mainly for wireless sensor networks. There are many of this kind such as IEEE 802.15.4 [13] standard, and the typical mechanism of them is to provide time slots in which CSMA and TDMA are dynamically selected to reduce frame collision [15] [16]. However, since they have been proposed for wireless sensor networks in which requirements for communication frequency are essentially different from WMNs, they cannot achieve the sufficient communication speeds required for WMNs.

To realize high-speed WMNs, Ding et al., proposed a scheme in [17] that combines the ADCA (Adaptive Dynamic Channel Allocation Protocol) and ICAR (Interference and Congestion Aware Routing protocol), where ADCA is an extension of MMAC [18] that distributedly negotiates channels for the multiple interfaces equipped on each node to reduce hidden terminal effects, and ICAR adaptively selects paths using dynamic metrics. However, although [17] is designed for the network with a gateway where the effect of interference is relatively small because all traffic goes through the gateway, ADCA cannot eliminate hidden terminal effects and so it reduces the interference using dynamic metrics.

CATBS(CSMA-Aware Time-Boundable Scheduling)[19] has been proposed as a method for solving the above problem and eliminate hidden-terminal effects in WMNs. CATBS is based on slotted CSMA, i.e., CSMA works within time-divided slots, and avoid collisions due to hidden-terminals by applying a schedule that assigns a slot for each link. Different from the previous studies, CATBS theoretically eliminates collisions due to hidden terminals by allowing detour paths in its joint routing and scheduling algorithm. Also, by introducing RTS/CTS in the slot boundaries, it is robust to the time drift on synchronizing time among nodes. As a result, CATBS achieves high-speed communications with low frame loss over WMNs.

However, one of the problems of CATBS comes from the interference model used in the scheduling scheme. The original scheduling scheme assumes a simple interference model called the single disk model in which the communication and the interference distances are the same. This is not a realistic property especially if CATBS works with high-speed communication links. In other words, the performance of CATBS will be significantly degraded with high-speed PHY protocols since the scheduling scheme does not match the physical property of communications.

The SINR model is widely known as a radio interference model close to reality [20]. The SINR (Signal to Interference and Noise Ratio) model regards the transmission signals as being received if the ratio of signal and noise (plus interference) is larger than a certain threshold. Note that, although SINR model is regarded as one of the standard models close to reality, if we design the scheduling problem based on SINR model, we need to consider all combinations of transmitting nodes to compute SINR so as to judge whether the transmission is succeeded or not, resulting in exponential computational time. Therefore, in the proposed method, we use the double disk model as a feasible interference model while being more realistic than the single disk model.

In this paper, we consider to use high-speed PHY in CATBS-based WMNs to raise the communication capacity of the networks. For this purpose, we first propose to introduce double-disk interference model in the scheduling scheme of CATBS. Note that double-disk interference model consists of two distances, i.e., the communication distance and the interference distance, and the latter is not easy to determine in the real environment. Thus, we next propose to determine the interference distance based on observation of IEEE802.11 beacons, which is transmitted with low-speed PHY protocol.

The reminder of this paper is organized as follows. In Sec. 2, we present CATBS, the baseline scheme of slotted-CSMA based WMNs. In Sec. 3, we extend CATBS by introducing double-disk interference model. In Sec. 4, we evaluate the proposed method. In Sec. 5 we introduce related work on joint routing and scheduling methods, and finally we conclude the work in Sec. 6.

2 CATBS: A SLOTTED-CSMA-BASED ARCHITECTURE OF WMNS

2.1 Overview

CATBS is a communication method for WMN that avoids hidden terminal problem, which is achieved with a combination of slotted CSMA and a scheduling method. In addition, the slotted CSMA used in CATBS is a little modified from the original CSMA. First, a single frequency channel is time-divided to create several virtually independent channels. Then, CSMA runs within each virtual channel. In the scheduling method, a virtual channel is allocated to each link such that hidden terminal problem does not occur. Since collision between adjacent nodes can be avoided by the carrier-sensing function of CSMA, our scheduling method only take the hidden-terminal effects into account. We define the interference model that considers radio interference due to hidden terminal problem and formulate it as an optimization problem that minimizes the effect of hidden terminal problem. Since the formulated problem is proven to be NP-hard, we obtain the solutions efficiently by reducing to PMAX-SAT.

2.2 MAC Protocol

The MAC protocol used in CATBS is a slotted CSMA with a little modification. The slotted CSMA is a mechanism in which we divide a frequency channel with a fixed time interval and run CSMA within each slot. Different from the original slotted CSMA, we do not use TDMA in slots at all because TDMA requires strict time synchronization. By avoiding to use TDMA, CATBS works with relatively loose time synchronization system, which significantly relaxes the restriction for the communication system.

In the MAC protocol used in CATBS, first, a single frequency channel is divided in time and multiple virtual channels are generated. Each virtual channel is called a slot. Then, CSMA runs inside the created slot. In order to operate CSMA, it is necessary to take a relatively large time per slot compared with TDMA. Each slot is given a number 1, 2, $\cdots$, k for identifying them, and it is switched in turn as 1, 2, ..., k, 1, 2, ... and so on. An example is shown in the Fig. 1. In Fig. 1, a single frequency channel is time-divided into k slots. Since two links in the relationship of hidden terminal problem transmit frames in different slots, the hidden terminal problem does not occur. In addition, RTS / CTS is used to avoid frame collision at the boundary of slots due to time synchronization error. Namely, when transmitting a data frame, if the transmission time is judged to exceed the boundary of the current slot, RTS is transmitted. After CTS is returned, nodes that received RTS or CTS wait for NAV period without transmitting data frames even if when the allocated slot comes. When the NAV period ends, the nodes start transmitting data frames.

2.3 Definitions

In order to formulate the scheduling problem, we begin with definitions. The network is represented by the directed graph $G = (V, E, C)$, where V is the node set, E is the link set, and C is the channel set. We define $e = (u, v, c)$ as

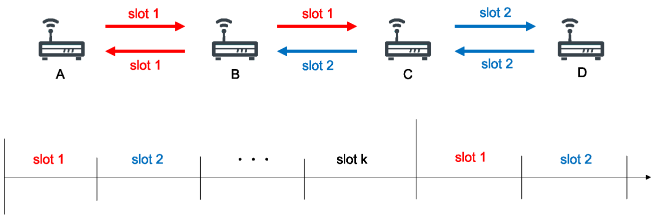


Figure 1: Virtual multi-channelization by time division

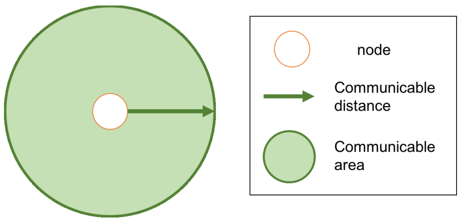


Figure 2: Communicable distance

the link to communicate using channel c from node $u \in V$ to $v \in V$. If there is a pair of links $e_1 = (u_1, v_1, c_1)$ and $e_2 = (u_2, v_2, c_2)$ in the hidden terminal relationship, it is called as an interference link pair. We denote the shortest path length from node u to v on graph G by $D^G_{(u,v)}$. Let S_G be the set of interference link pairs in G, which is called as the collision degree of graph G. The scheduling problem of CATBS aims at minimizing the number of collision link pairs $|S_G|$ by removing links in G and output the graph G' that is free from hidden terminal problem.

2.4 Single-disk Interference Model

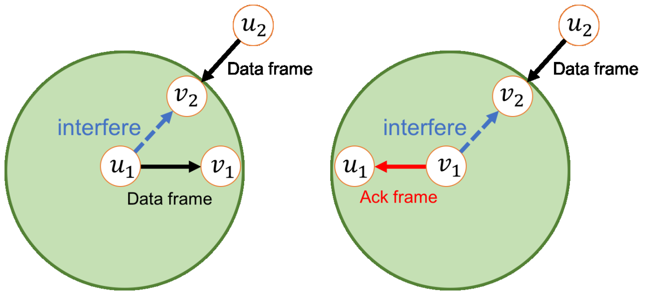
CATBS uses a single disk model as an interference model to simplify the situation where radio interference occurs. In the single disk model, when a node communicates with some other nodes, the distance with which the communication succeeds is called the communicable distance r, and the area inside the circle of radius r is called the communicable area. In the single disk interference model, we assume that there is no radio interference outside the communicable area.

2.5 Defining Collision Link Pairs Based on Single Disk Model

Collisions under single disk model are modeled as two types: collisions invoked by data frames, and those invoked by Ack frames. We show an example of those two types of collisions in Fig. 3. In Fig. 3(a), a data frame from u_1 to v_1 collides with a frame from u_2 to v_2. In Fig. 3(b), an Ack frame sent from v_1 collides with a frame from u_2 to v_2. Those two types of collisions are formally defined as follows.

Type 1: collision with data frames occur if all the following conditions are met.

1. $c_1 = c_2$
2. $(u_1, u_2, c_1) \notin E$
3. $(u_1, v_2, c_1) \in E$



(a) Data frame interferes (b) Ack frame interferes

Figure 3: conditions of interference link pairs

Type 2: collision with Ack frames occur if all the following conditions are met.

1. $c_1 = c_2$
2. $(u_1, u_2, c_1 \notin E)$
3. $(v_1, v_2, c_1) \in E$

2.6 Formulation of Scheduling Problem

In the scheduling problem formulation of CATBS, we first consider the graph G that consists of every possible links $e = (u, v, c)$ where $u, v \in V$ and $c \in C$, i.e., we include links with every combinations of u, v, c. Then, we choose a subset of links in G and output the schedule $G' = (V, E', C)$ where $E' \subseteq E$. Note that, from the restriction of the default router architecture that each node has only one transmission queue, the number of slots assigned to a node is limited to one. Namely, the incoming and the outgoing links of the same node must belong to the same slot. Also note that the pair of links in the relationship of collision has already defined. Our goal is to minimize the *interference level*, which is defined as the number of collision link pairs in G'.

If the number of slots in the schedule increase, CATBS would face in severe end-to-end delay due to the time to wait active slot at each node. To prevent the delay in scheduling, CATBS allow to use paths that are not the shortest-paths between the source and destination node pairs. Specifically, in the scheduling, CATBS chooses a set of links for G' such that, for each pair of source and destination (s, d), the length of the shortest path in G' is equal to or less than that in G + k, where k is the predefined stretch factor. More formally, if we let $\delta^G_{s,d}$ be the shortest-path length from s to d in G, $\delta^{G'}_{s,d} \leq \delta^G_{s,d} + k$. Namely, by allowing k-hop longer paths than the shortest path, CATBS reduces the number of slots required to achieve zero-collision. As above, the formal description of the scheduling problem in CATBS is given as follows.

The Scheduling Problem in CATBS

Input: A graph $G = (V, E, C)$, A set of collision link pairs S_G.

Output: A schedule $G' = (V, E', C)$ where $E' \subseteq E$

Subject to: $\delta^{G'}_{s,d} \leq \delta^G_{s,d} + k$, and every node does not have more than 2 assigned slots.

Minimize: Interference level $|S_{G'}|$

2.7 Algorithm to Solve the Problem

In the literature the scheduling problem was proven to be NP hard. Therefore, it takes a huge amount of time to find the optimal solution. In CATBS, in order to find an approximate solution efficiently, we reduce the scheduling problem to PMAX-SAT. PMAX-SAT is a traditional NP-hard optimization problem, and recently, there held a contest of good solvers for large-scale PMAX-SAT problems, for which several excellent solvers have been developed so far. CATBS intends to use one of those excellent solvers of PMAX-SAT.

In PMAX-SAT, we let $x_1, x_2, ..., x_n$ be logical variables that take values true (1) or false (0). Let $\overline{x_1}$ be the inverted value of logical variable x_1. A logical expression such as $(x_1 \vee x_2)$ obtained by connecting several logical variables with OR operators $(\vee)$ is called a clause. We call logical expressions in which we connect clauses with AND operator $(\wedge)$ as a canonical normal form (CNF) formulas, e.g., $(x_1 \vee x_2) \wedge (\overline{x_1} \vee x_3)$. For each of the logical variables $x_1, x_2, ..., x_n$ in the given CNF formula we assign a logical value true(1) or false(0). The SAT(SATisfiability Problem) problem is defined as a task to output whether there is a set of true/false assignment that satisfy the given CNF formula. The problem to maximize the number of satisfied clauses is called MAX-SAT (MAXimum SATisfiability problem). As a further extension of MAX-SAT, we define Partial MAX-SAT (PMAX-SAT). For a given CNF formula $f(x_1, x_2, ..., x_n) = g_h(x_1, x_2, ..., x_n) \vee g_s(x_1, x_2, ..., x_n)$ where $g_h(\cdot)$ and $g_s(\cdot)$ are also CNF formula called hard and soft clauses, respectively, PMAX-SAT maximize the number of satisfied clauses in soft clauses g_s under the constraint that all the hard clauses g_h are satisfied. The formal description of PMAX-SAT is as follows.

PMAX-SAT

Input: CNF formula $f = g_h \vee g_s$.

Output: 0/1-Assignment of logical variables.

Maximize: The number of satisfied soft clauses.

Subject to: All hard clauses are satisfied.

We make a reduction from the scheduling problem of CATBS to PMAX-SAT. The constraints of CATBS such as the increase of path length are expressed by the hard clauses, and optimization criterion, i.e., the interference level, is expressed by the soft clauses. Specifically, for the input of the scheduling problem $G = (V, E, C)$, we define logical variables $l_{u,v,c}$ for all links included in E, where $l_{u,v,c}$ takes true if the corresponding link exists in G' and false otherwise. Although we omit the detail due to paper limitation, the hard clauses g_h are created such that they all are satisfied only if all the constraints in the scheduling problem are satisfied. See reference [11] for detail. The soft clauses g_s consists of a set of clauses $(\overline{l_1} \vee \overline{l_2})$, each of which corresponds to each collision link pair (l_1, l_2) in G. This clause does not satisfy only if both links are included in G' and invoke collision. As a result, once the PMAX-SAT is solved, the set of binary variables $l_{u,v,c}$ determines the schedule G', with which the interference level $|S_{G'}|$ is minimized. When this formula is a hard clause and the hard clause is true, the graph G' satisfies the constraints of the optimization problem. Next, in the soft clause, the logical expression $(\overline{l_1} \vee \overline{l_2})$ for all the link pairs included in the set of link pairs S'_G in the hidden terminal problem relationship Take it with an AND operator. $(\overline{l_l} \vee \overline{l_j})$ takes false if both link pairs in hidden terminal problem relationships are not restricted on graph G'. That is, the number of logical expressions that take false matches the collision degree on graph G'. Then, by allocating logical variables that takes as many true as possible in soft clauses, graph G' eith lowest collision degree is output.

2.8 The Problem with CATBS-based WMNs

CATBS uses the single disk model to simplify the situation of hidden terminal problem. However, wireless communication gets more vulnerable against noise when the communication speed gets higher. Specifically, with high-speed links, the communicable distance goes shorter while the interference distance stays the same. As a result, when we assume high-speed links, schedules based on the single-disk model are no more possible to treat collisions appropriately. From this reason, we in this paper introduce the double-disk interference model to compute schedules more suitable for high-speed wireless communications.

3 THE PROPOSED METHOD

3.1 overview

We propose a new scheduling method to reduce radio interference in WMNs with high speed links. In our proposal, we use a double disk model as a more realistic interference model than the single disk model. In the double disk model, two distances, i.e., the communicable distance and the interference distance are defined such that two nodes can communicate with each other if they are located within the communicable distance, but a radio from a node located within the interference distance disturbs it. Our scheduling method is designed for distributed environment. First, we describe the method to identify the nodes within the range of the interference distance. We next give the algorithm to compute the collision link pairs from that information. After those steps, we can compute the schedule based on the double disk model.

3.2 Concept of proposed method

We intend to realize autonomously decentralized networks in which each node executes schedules and forwarding paths by means of running routing protocols. In the schedule calculation, each node requires the information of the network topology, so that a routing protocol such as OLSR is used to perform the distributed control. In order to realize the autonomous distributed scheduling using a routing protocol, each node needs to grasp the node located in the interference area under the double disk model. However, since the interference distance is larger than the communication distance especially with high-speed links, this information cannot be grasped by control messages of routing protocols. Also from the proactive routing protocol, each node cannot grasp the distance information to identify the nodes in the interference distance because this kind of routing protocols only treats the topology of the network.

To grasp the nodes within the interference area, we use beacons that is periodically transmitted by every node with low communication speed. By observing all beacons received at every node, it grasps a set of nodes from which beacons can be received with high probability. Each node regards that the set of nodes are within the interference area. Since beacons are specified to transmit with minimum possible speed, the interference distance is supposed to be far larger than communicable distance.

In order to perform the distributed control using routing protocols, it is necessary that the calculation time of the schedule should be short and schedules should be computed even on a terminal with low capability. Simultaneously, we must design a joint routing and scheduling protocol in which schedules and routing tables are surely computed and the routing scheme works. In this paper, we simply introduce a feasible design of the joint routing and scheduling protocol that works in the distributed environment, and propose the method that can incorporate with the protocol.

3.3 Routing and Scheduling Protocol Framework

In order to execute the proposed scheduling method autonomously and distributedly, each node must collect the information required for scheduling. To compute schedules, we must collect two sorts of information, i.e., the network topology, and a set of collision link pairs. The network topology can be collected by using a proactive routing protocol such as OLSR. Therefore, we in this paper describe only how to collect collision link pairs.

In our joint routing and scheduling protocol, each node first computes its schedule (as we mentioned before, a schedule G' is a subgraph of the network topology G), and computes the shortest paths on G' to build its routing table. To compute a schedule, we must collect the network topology and the set of collision link pairs. To compute the latter, each node observes beacons and grasps a set of nodes within the interference area. On the other hand, the nodes within the communicable distance is known from the network topology. By sharing those two sorts of information with the surrounding nodes, each node can compute the collision link pairs. The set of collision link pairs computed at every node is shared over the network, and all nodes in the network obtains the set of collision link pairs as a result. Since every node know the topology and the collision link pairs of the whole network, a joint routing and scheduling protocol as described above is able to design. As the framework we apply the proposed scheduling algorithm, we assume this kind of network protocols.

3.4 Defining Collision Link Pairs Based on Double Disk Model

In the proposed method, we apply double disk model as the interference model to take the radio interference under high-speed links into account. The double disk model is defined

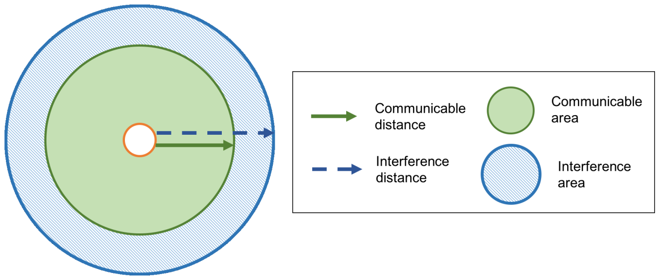


Figure 4: Interference distance

as two disks with different radius, which represents the communicable area and the interference area, respectively. In this interference model, the communicable distance (i.e., radius) means that two nodes are communicable with each other if other radio does not exist. Similarly, the interference distance means that the communication from a node s to d fails if d is within the interference distance from a node i on which transmission is ongoing. Generally, in high-speed links, the communicable distance is far smaller than the interference distance.

In order to formulate the scheduling problem, we make definitions of collision link pairs. For the network represented by a directed graph $G = (V, E, C)$, we assume two links as $e_1 = (u_1, v_1, c_1)$ and $e_2 = (u_2, v_2, c_2)$, and define the condition in which e_1 interferes e_2 due to the hidden terminal effect. Here, we denote the set of nodes located in the interference area of u_1 by N_{u_1}.

As in the case of CATBS, collisions are classified into two patterns: one is the case where data frames collide to other frames, and the case Ack frame collides. An example is shown in Fig. 5. In Fig. 5(a), the data frame from u_1 to v_1 collides to another frame from u_2 to v_2. In contrast, In the case of Fig. 5(b), the Ack frame from v_1 to u_1 collides to another frame from u_2 to v_2. The formal representation of those two type of collision cases are written as follows.

Type 1: collision with data frames occur if all the following conditions are met.

1. $c_1 = c_2$
2. $u_2 \notin N_{u_1}$
3. $v_2 \in N_{u_1}$

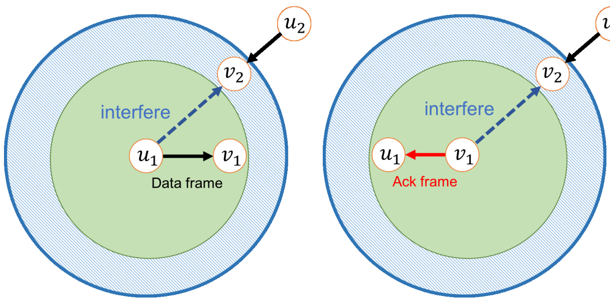
Type 2: collision with Ack frames occur if all the following conditions are met.

1. $c_1 = c_2$
2. $u_2 \notin N_{u_1}$
3. $v_2 \in N_{v_1}$

4 EVALUATION

4.1 Evaluation method

We evaluate the effectiveness of the proposed method in high speed communication environment through simulation



(a) Data frame interferes (b) Ack frame interferes

Figure 5: Conditions of interference link pairs

with the proposed scheduling method using network simulator Scenargie[21]. Since the proposed method uses the Double Disk Model, it is necessary to properly determine the communicable distance and the interference distance. To determine those values, we conducted a preliminary experiment by simulation.

The proposed method is designed to perform scheduling calculation using information that can be acquired in an autonomous distributed environment. As we mentioned previously, if data frames can be received from an adjacent node with high probability, we regard that the node is within the range of the communicable distance. On the other hand, if a beacon frame can be received from a node, we regard that the node is within the interference distance range. In this evaluation, we evaluate the communication performance by applying a pre-calculated schedule instead of calculating schedules in real time due to computational time for scheduling. In order to determine the appropriate communicable distance and the interference distance used in the schedule calculation in advance of performance evaluation, we carried out a preliminary simulation to determine those two distances.

With preliminary simulations, we first retrieve for each node a set of nodes within the communication and interference distance, respectively. Specifically, we run simulation with the scenarios planned in traffic simulation, find the set of nodes from which more than 80% of data frames are received, and identify the set as within communication distances. Similarly, we find the set of nodes from which more than 80% of beacon frames are received, and identify it as the nodes within interference distances. Those two sets of nodes are used in computing schedules, i.e, we create a PMAX-SAT formula from those sets and the topology, and compute a schedule by solving the PMAX-SAT problem. As PMAX-SAT solver, we used qmax-sat developed by Koshimura[22].

As a simulation scenario that is common in both the preliminary simulation and the traffic evaluation given in Sec. 4.3, we located 100 nodes in the 2300 $\times$ 2300 meter rectangular field, and generate 40 flows with randomly selected source and destination nodes. In the flows, packet size is 1500 Bytes and the transmission rate is 1 Mbps each. Each node communicates with others under IEEE802.11g standard with 48 Mbps speed and 20 dBm transmission power. According to the standard, beacon frames are transmitted with 1 Mbps speed. We generate flows from the beginning of the scenario, and measure the performance in the interval of stable state from 60 Sec to 600 Sec.

We first evaluate the performance of schedules obtained with our method, and next made a traffic evaluation to examine the communication performance. In the former evaluation, we investigate the number of slots necessary to achieve zero collision. In the proposed method, double-disk model is used as the interference model. Therefore, it is conceivable that the number of slots required for zero collision goes larger than CATBS. In the evaluation, it is clarified how much the number of slots is needed compared with CATBS.

In traffic simulation, we evaluate the communication performance of the proposed method in comparison with CATBS. We generate 40 flows with randomly-selected sources and destinations in various transmission rates. Same as the preliminary simulation, we measured the communication performance in the time interval from 60 Sec to 600 Sec to avoid capturing the unstable state of networks. We ran the simulation 10 times for each parameter values and use the average of it.

4.2 Scheduling performance

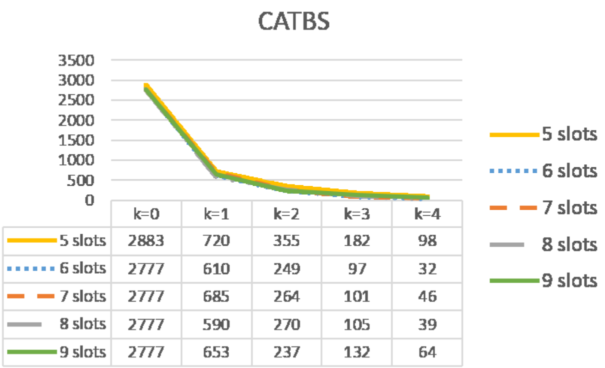
We examine the number of slots required to achieve zero-collision for each value of stretch factor k over the random topology. As shown in Fig. 6(a), CATBS could not compute zero-collision schedule with $k \leq 4$ even under as large as 9 slots. In contrast, Fig. 6(b) shows that the proposed method computes a zero-collision schedule even for the 5-slot case with $k \leq 4$. This is mainly because the carrier-sense distance in the proposed method, which is set to the same value as interference distance, is larger than CATBS. By introducing the double-disk model, not only the interference range but also the carrier-sense range increases. This improves the spacial efficiency, resulting in zero-collision schedule under smaller number of slots.

From above, we conclude that the proposed method reduces the required number of slots to obtain a zero-collision schedule. This means that the favorable effect of larger carrier sense distance is larger than the inconvenient effect of larger interference distance. For practical use, the proposed model is more favourable than CATBS in that zero-collision schedule is easier to obtain.

4.3 Communication performance

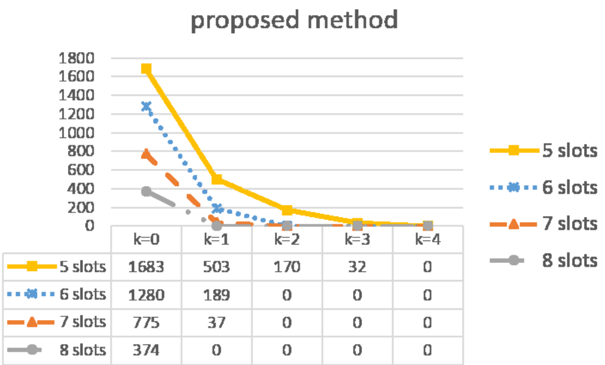
We compare the communication performance of the proposed method with CATBS using network simulator Scenargie [21]. We first compare the performance under several parameter values within the proposed method and CATBS, respectively, and finally compare those two with the best-performance parameters.

First, we show the results on CATBS in Fig. 7. Since CATBS could not achieve zero-collision, we examined the results of 4-5 slots with small k, and added the results of 3 slots for reference. From the results, the case of 4 slots with $k = 0$ leads the best performance. For each number of 4-5 slots, the case of $k = 0$ is better than $k = 1$, meaning that the penalty of longer paths is larger than the loss of collision with shorter paths in CATBS. Note that, with $k = 0$, although the 5-slot



	k=0	k=1	k=2	k=3	k=4
5 slots	2883	720	355	182	98
6 slots	2777	610	249	97	32
7 slots	2777	685	264	101	46
8 slots	2777	590	270	105	39
9 slots	2777	653	237	132	64

(a) Interference levels based on Single Disk Model (CATBS)



	k=0	k=1	k=2	k=3	k=4
5 slots	1683	503	170	32	0
6 slots	1280	189	0	0	0
7 slots	775	37	0	0	0
8 slots	374	0	0	0	0

(b) Interference levels based on Double Disk Model (proposed method)

Figure 6: Scheduling

case exhibits almost the same thoughput performance as the 4-slot case, delay paerformance is degraded. This is because, in 5-slot cases, smaller capacity of links due to larger number of slot causes queuing delay. Anyway, the case of 4-slot with $k = 0$ was the best in CATBS.

Next, we compare the results on the proposed method in Fig. 8. From the results on the scheduling algorithm, we identified the cases of 6-8 slots with $k \leq 2$ as the suitable parameter values in practical use. Among the cases of 6-7 slots, the case with $k = 2$ has the best performance. This means that collision reduction achieved by longer paths effectively works in the proposed method, which is a different trend from CATBS. With 8 slots, the case of $k = 1$, the smallest k with zero-collision schedule, has the best performance, where the trend is the same trend as 6-7 slot cases. The best case is with 6 slots and $k = 2$, since smaller number of slots naturally improves both delay and capacity, and also since sufficiently large k achieved zero-collision.

We compared the performance of CATBS, CSMA and the proposed method. We use the case of 4 slots with $k = 0$ for CATBS, and two cases of 6 slots with $k = 2$ and 8 slots with $k = 1$ for the proposed method. See Fig. 9 for the results. The proposed methods marks higher performance than CATBS although the number of slots is larger than CATBS. This is mainly due to the effect of achieving zero-collision by offering longer paths. CSMA is lower than the proposed methods in both throughput and delivery ratio although delivery delay is always low. This is due to high frame loss ratio caused by hidden terminals in CSMA. It is concluded that the proposed method improves the communication performance under high-speed links by introducing the double disk model.

Finally, we compared the performance in TCP communications. The simulation scenario is the same except that we generate 60 TCP flows with random source and destination nodes. The results are shown in Fig. 10(a)(b). Although the delivery ratio of the proposed method is higher than CATBS and achieves almost 100%, the throughput is lower. This is due to low link capacity of the proposed method, i.e., since the number of slots in the proposed method is 1.5 times larger than CATBS, link capacity per link is 1.5 times lower, and throughput is 1.5 times lower as well. This offers a weakness of the proposed method that requires a larger number of slots in expense of reducing packet loss.

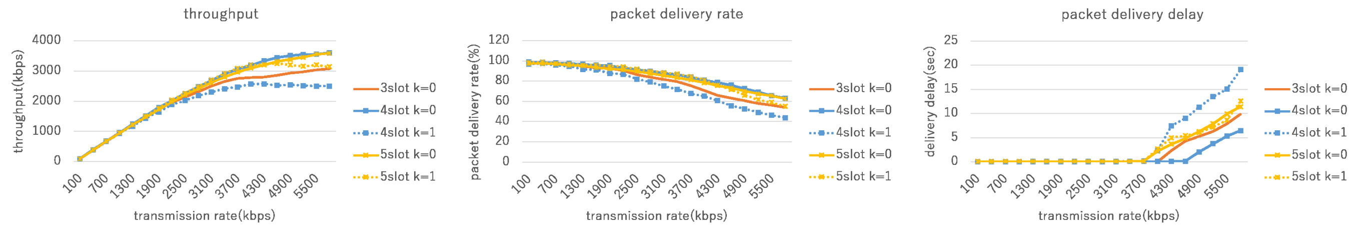
5 RELATED WORK

we already have several joint channel assignment and routing schemes in the literature. Since channel assignment is essentially the same as slot allocation, they are closely related to CATBS. Alicherry et al. proposed a joint channel assignment and routing method that tries to optimize throughput in WMNs in multiple gateway scenarios by combining Linear Programming (LP) with their heuristic algorithms [24]. However, since they do not assume the property of CSMA, i.e., they assume that every adjacent link pair interferes with each other, the required number of channels grows too large so that they cannot achieve collision-free channel assiignment even with as many as 12 orthogonal channels. Mohsenian-Rad et al. proposed a joint channel assignment and routing method that considers path-length constraint in general WMNs by applying Mixed Integer and Linear Program (MILP) [23]. However, since they assume that RTS/CTS is always used and that it works perfectly under the single-disk interference model, their method has less efficiency due to exposed terminal problems, and further suffers from interference in high-speed environments due to the gap between the single-disk interference model and reality. By applying more precise collision model based on CSMA on top of double-disk model, the proposed method achieves more efficient collision-free schedule.

6 CONCLUSION

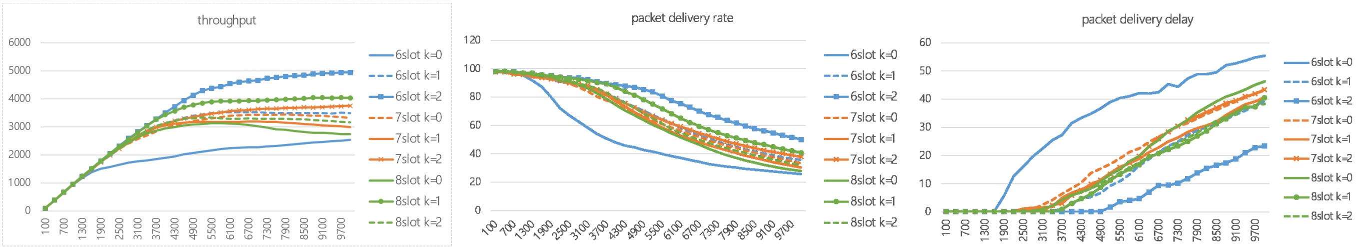
In this paper, we proposed a new scheduling method to reduce radio interference under high speed communication. By using the double disk model as an interference model, more precise treatment of radio interference is possible compared to the conventional single disk model. The proposed scheduling algorithm based on the double disk model, a large part of collisions that are involved in the schedule in CATBS are avoided.

As a result of the evaluation, we confirmed that, by using the proposed scheduling method, radio interference under high speed communication is reduced and communication performance is improved. From this fact, modeling using the double disk model is more suitable than using the single disk model under high-speed communication. In addition, the proposed method uses beacon reception status to determine the



(a) CATBS throughput (b) CATBS Packet Delivery Rate (c) CATBS Packet Delivery Delay

Figure 7: Comparing Performance of CATBS Under Parameter Variation



(a) propose method Throughput (b) propose method Packet Delivery Rate (c) propose method Packet Delivery Delay

Figure 8: Comparing Performance of Proposed Method Under Parameter Variation

interference distance. Our evaluation in this paper shows that we can grasp the interference distance with this approach, and indicates the possibility that we could design autonomous distributed joint routing and scheduling scheme in the future.

One of the future tasks is to apply more realistic interference models in scheduling. The double disk model considers the interference range in addition to the single disk model. However, the most realistic interference model called SINR model judges whether frames are successfully received or not from SINR (Signal and Interference plus Noise Ratio). SINR-model-based scheduling would offer more accurate scheduling and would further improve the spacial efficiency of wireless communications.

In addition, we note that the beacon-based determination of double-disk-model distances proposed in this paper cannot determine the suitable distances for various communication speed. This paper showed that the proposed method determines the two distances of the double-disk model suitable for 48Mbps speed. However, the suitable distances are in fact different for each speed. How to determine them for each communication speed and modulation method is also left in the future.

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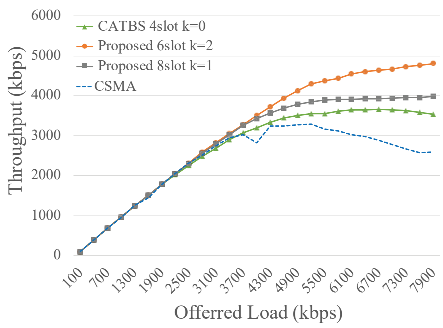
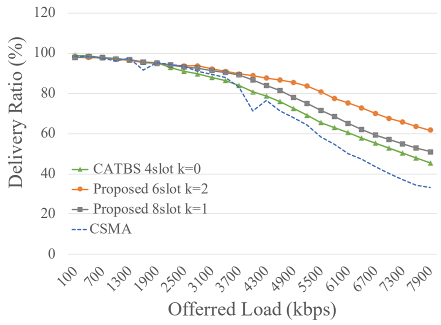
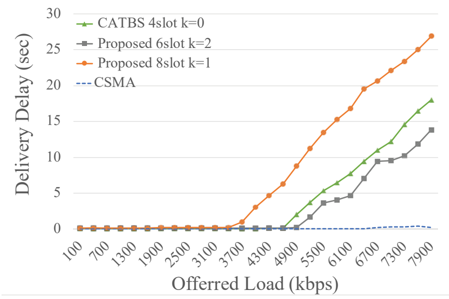


(a) Throughput

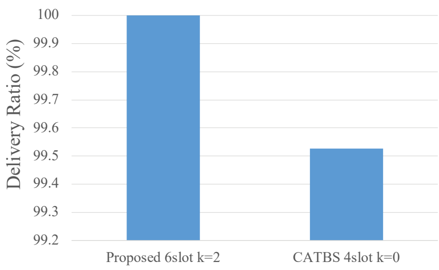


(b) Packet Delivery Rate

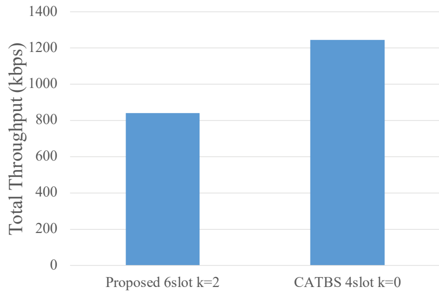


(c) Packet Delivery Delay

Figure 9: CBR Performance Comparison



(a) Packet Delivery Rate



(b) Throughput

Figure 10: TCP Performance Comparison

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