A Distributed Multi-Channel MAC Protocol for Ad Hoc Wireless Networks

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Abstract

This paper proposes a novel distributed multi-channel medium access control (MAC) protocol using fast and slow hopping sequences with dual radio interfaces. Specifically, one interface follows fast hopping and is primarily for transmission, and the other interface follows slow hopping and is generally for reception. The proposed protocol, which is in line with the IEEE 802.11 MAC strategies, is based on the multiple rendezvous approach and able to enhance the network performance and resolve the congestion. An analytical model is developed to evaluate the network performance in terms of the aggregate throughput. Furthermore, the maximum saturation throughput and the upper achievable throughput are computed. Simulations using network simulator-2 (ns-2) are conducted to validate the analytical model and demonstrate the significant enhancement of the proposed protocol in single- and multi-hop networks.

Index Terms

Multi-channel networks, frequency hopping sequence, IEEE 802.11 networks, medium access control

1 INTRODUCTION

Ad hoc networks are cost-effective and easy to deploy. However, the network performance of ad hoc networks is limited due to the interference among nodes. Many

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schemes and technologies have been proposed to improve the network performance such as using smart antennas, exploiting multiple orthogonal channels, and improving spatial reuse. Integrating one or more of these techniques provides further capacity improvement (e.g., using multiple channels with power control [1] [2]). On the other hand, a significant amount of research has been conducted to maximize the utilization of the available channels [1], [3]–[10]. Using multiple, orthogonal channels in the unlicensed spectrum can improve the network capacity because multiple transmissions can take place on multiple channels, e.g., three orthogonal channels are defined in the 2.4-GHz band and 12 channels are defined in the 5-GHz band [11], [12].

Some multi-channel medium access control (MCMAC) protocols have been proposed to use all of the available channels for ad hoc networks to enhance the network performance. MCMAC protocols can be generally classified into two categories based on their operations [13], i.e., single rendezvous (SR) and multiple (parallel) rendezvous (MR) protocols. In SR-MCMAC protocols, one agreement made between a transmitter and a receiver occurs over only one channel at any time, whereas, in MR-MCMAC protocols, multiple agreements made between different transmitter-receiver pairs occur over multiple channels at the same time. Thus, MR-MCMAC protocols outperform SR-MCMAC protocols [13].

SR-MCMAC protocols are further classified into three different operations [13]. First, common hopping SR-MCMAC protocols in which all nodes follow the same hopping sequence and hop between channels, e.g., the channel-hopping multiple access (CHMA) protocol [14] and the hop-reservation multiple access (HRMA) protocol [15]. Although nodes need only one interface, frequent switching between channels (i.e., the dwell time is equal to the RTS transmission) and tight global clock synchronization are required in these protocols [13]. Another issue should be addressed in these protocols is the busy receiver problem [13], which is also termed the missing receiver problem [16].

The second set of SR-MCMAC protocols is known as the split phase protocols in which time is slotted. A slot is divided into two phases. The first phase is the control phase in which the nodes meet on a predefined control channel to make agreements. In the second phase (the data phase), successful pairs tune to their agreed upon channels and exchange data [17]–[19]. For example, the multi-channel MAC (MMAC) protocol

[17], which uses the Ad Hoc Traffic Indication Messages (ATIM) window defined in the IEEE 802.11 for the power saving mechanism (power management), falls in this set. During the ATIM window, nodes tune their radios to the known channel. A pair of nodes select a channel by exchanging ATIM/ATIM-ACK/ATIM-RES packets. After the ATIM window, successful pairs switch their radios to the agreed channels. Then, source nodes start competition using the IEEE 802.11 MAC standard. MMAC solves the multi-channel hidden terminal problem by synchronization.

The third set of SR-MCMAC protocols is known as the dedicated control channel protocols in which one channel is dedicated for control and broadcasting packets and the remaining channels are data channels for data transmissions. The main disadvantage of using the dedicated control channel protocols is the congestion on the control channel [13], [17], [20], [21]. However, it does not require clock synchronization and is able to fully support broadcast information because all of the nodes listen to one channel all the time [1], [2], [9], [21], [22]. Examples are the dynamic channel assignment (DCA) protocol [9] and the multi-channel MAC protocol with hopping reservation (MMAC-HR) [22]. In the DCA protocol, nodes exchange control packets over the control channel to reserve data channels. Channel selection is based on the channel usage lists (CULs) of the nodes. However, using CULs leads to poor channel utilization and introduces a new issue in multi-channel networks called the multi-channel exposed terminal problem because nodes do not have full knowledge of channel condition [22]. In MMAC-HR, nodes hop between data channels, and source nodes reserve data channels for their transmission and then compete the data channels using the IEEE 802.11 MAC protocol. Using multiple channels with transmission power control (TPC), such as the DCA with power control (DCA-PC) protocol [1] and distributed power control over multiple channels [2], can further enhance the network performance.

The SR-MCMAC protocols suffer from the congestion on the common channel because a single agreement are made at any time [13]. MR-MCMAC protocols are therefore proposed to make multiple agreements at the same time to resolve the congestion on the common channel [3], [4], [23]. Examples include the Slotted Seeded Channel Hopping (SSCH) protocol [4] and the multi-channel MAC (McMAC) [3] protocol. Both protocols employ only one radio interface per node, which independently hops between channels. In order to send a packet to the receiver, the sender must synchronize with the receiver. SSCH employs an optimistic synchronization technique, and McMAC is based on a pairwise synchronization [24]. Therefore, the sender deviates from its default hopping sequence to meet the receiver. As a result, the busy receiver problem (the missing receiver problem) occurs [16].

A comparison among different MCMAC protocols is given in [13]. In [7], many protocols using multiple channels in order to improve the network performance have been discussed and classified. In the Hybrid Multi-channel Protocol (HMCP) [12], [25], it is required one interface be fixed and the second interface be switchable, which resolves the congestion over the control channel. The fixed interface considers only the node distribution over channels to switch on for the long term. Generally, the performance of this protocol depends on the traffic pattern over channels. This can lead to performance degradation because the channel assignment of the fixed interfaces is unaware of the traffic load. Fig. 1 shows the disadvantage of static assignment, where the number in the parenthesis is the channel number assigned to the fixed interface (i.e., the solid lines between two nodes mean that the nodes can communicate using their fixed interfaces, and the dashed lines between the source and destination nodes indicate that the source can communicate with its destination by switching its switchable interface to meet the fixed interface of the destination). If node A needs to communicate with node B, the switchable interface of node A tunes to the fixed interface's channel of node B, which is on Channel 2. At the same time, node G has packets for node F, and nodes B and D are required to transmit packets to nodes D and F, respectively; as a result, the switchable interface of node G switches to Channel 2, and nodes B and D use their fixed interfaces to communicate with nodes D and F, respectively, because their fixed interfaces are on Channel 2. Thus, the channel bandwidth is wasted due to unbalanced traffic load [26]. Moreover, a routing metric is developed in [12], [25] to engage the switching delay. Although existing wireless interfaces can switch between channels with delays of 130 μs [27], it is expected that the channel switching delay of wireless interfaces will be reduced to 40-80 μs [4].

In this paper, we propose a novel multi-channel MAC protocol [28] based on the parallel rendezvous approach (i.e., independent frequency hopping). There are several

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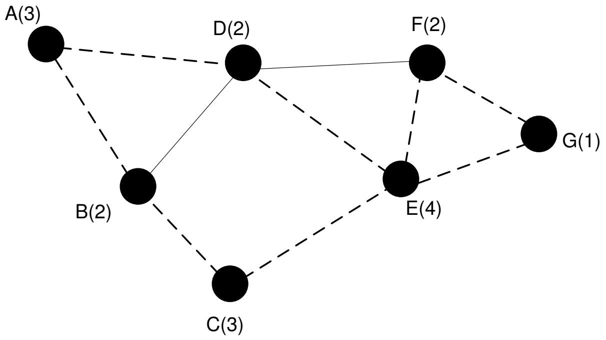

Fig. 1: The problem of static channel assignment.

advantages of the proposed protocol: 1) utilization of multiple channels by allowing multiple transmissions at the same time; 2) the ability to avoid congestion because the proposed protocol does not need a dedicated control channel and enables wireless nodes dynamically switch among channels; 3) the contention level on any channel is much less compared with SR-MCMAC protocols; and 4) avoiding the busy receiver problem, which has not been addressed in other multiple rendezvous protocols including the McMAC [3] and SSCH [4] protocols because one interface in our protocol never deviates from its hopping sequence. Moreover, the proposed protocol does not change the IEEE 802.11 legacy and employs two half-duplex interfaces. One interface follows fast hopping and can deviate from its hopping sequence to communicate with other wireless nodes, and the other interface follows slow hopping and never deviates from its hopping sequence. In general, the fast hopping interface is for transmission and the slow hopping interface is for reception; therefore, a node can work as a full-duplex system on different channels.

The main contributions of this paper can be summarized as follows:

- We present a new MCMAC protocol which improves the network capacity using independent frequency hopping. The proposed protocol follows the parallel rendezvous approach and does not change the IEEE 802.11 standard.
- An analytical model is developed and validated using the network simulator (ns-2) for single-hop networks.
- The maximum saturation throughput of each channel can be achieved by comput-

ing the optimal transmission probability considering the number of channels. In addition, we derive the upper limit throughput when the number of channel is large.

- The proposed protocol works well in multi-hop networks using the Dynamic Source Routing (DSR) protocol.

The remainder of this paper is organized as follows. First, we describe the system model in Section 2. In Section 3, we present the proposed MCMAC protocol. Section 4 presents the analytical model to evaluate the proposed protocol, followed by the validation of the analytical model in Section 5. The maximum saturation throughput and throughput limit are computed in Sections 6 and 7, respectively. In Section 8, simulation results of multi-hop networks are illustrated. Finally, the conclusion and future work are given in Section 9.

2 SYSTEM MODEL

Consider that k orthogonal channels are with an equal bandwidth. All nodes are equipped with two half-duplex interfaces, and both interfaces are able to switch between multiple channels. The two interfaces do not share the same channel at any time and do not interfere with each other so that they can work simultaneously. One interface follows a slow hopping sequence and the other one follows a fast hopping sequence. In addition, the slow hopping interface never deviates from its hopping sequence to avoid the busy receiver problem [13]. In general, the fast hopping interface is for transmission while the slow hopping interface is for reception. However, the fast hopping interface is able to receive any packet (e.g., a broadcast packet). For the slow hopping interface, it transmits HELLO and broadcast packets. In addition, a transmitter can communicate with its receiver if their slow hopping interfaces share the same channel.

Each node is assumed to be synchronized only with its neighboring slow hopping interfaces. Note that the proposed protocol does not require a global synchronization, but requires a pairwise synchronization between neighbors, which is similar to the existing parallel rendezvous protocol [3]. To facilitate a single-hop (pairwise) synchronization[1], each node transmits a HELLO packet through its slow hopping interface when switching to a new channel. The HELLO packet contains three fields: the first field is the default seed; the second field is the local clock time of the node; and the third field contains the remaining time to switch to the next channel. When a node receives any HELLO packet, the receiving node creates or updates a record of the transmitting node.

The nodes within the communication range of each other are able to communicate over one hop transmission, so a transmitting node must meet (rendezvous) with a receiving node over a channel. If both the slow hopping interfaces of the transmitting and receiving nodes share the same channel, the transmitting node starts the data transmission using its slow hopping interface (e.g., nodes C and D during slot i shown in Fig. 2 in which node C is the transmitter and node D is the receiver). Otherwise, the transmitter deviates its fast hopping interface to meet the slow hopping interface of the receiver (e.g., the fast hopping interface of node D switches to Channel 4 to meet the slow hopping interface of node A as shown in Fig. 2). Consequently, multiple communications can take place at the same time and a node is able to concurrently transmit and receive over different channels. Each transmission follows the IEEE 802.11 MAC scheme and the distributed coordination function (DCF) protocol [11], showing that we do not modify the IEEE 802.11 MAC strategies. In multi-hop networks, a routing protocol is required to determine the routing path and each interface after switching must sense a channel for a period of time before attempting to transmit to avoid the multi-channel hidden terminal problem [17]. In Section 8, we evaluate the proposed protocol in multi-hop networks.

3 DYNAMIC SWITCHING PROTOCOL (DSP) USING FREQUENCY HOPPING

In this section, we propose a novel MCMAC protocol called dynamic switching protocol (DSP). The proposed protocol is based on the parallel rendezvous approach (i.e., independent frequency hopping) and uses two interfaces that can switch dynamically. One

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[1] Pairwise synchronization techniques are scalable with different network densities and achieve a better level of synchronization especially for operating MCMAC protocols [24] [29]. However, this paper is not concerned about any implementation of pairwise synchronization protocols.

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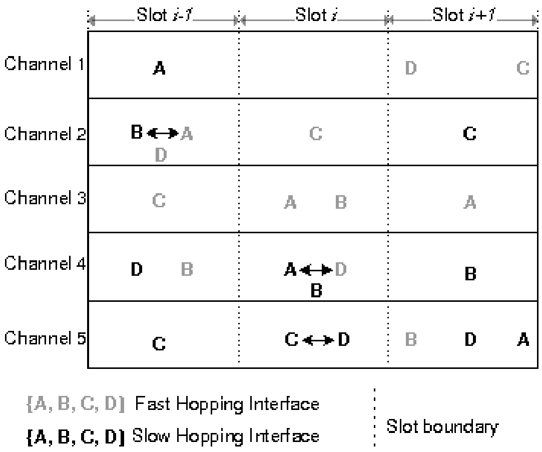

Fig. 2: Instances of the channel activities using the proposed protocol.

interface follows fast hopping while the other one follows slow hopping. The proposed protocol is distributed and based on the IEEE 802.11 MAC strategies.

All nodes randomly generate hopping sequences for their slow hopping interfaces, and these interfaces never deviate from their hopping sequences. Nodes should only synchronize with the slow hopping interfaces of each other using pairwise synchronization as presented in Section 2, and it will lead to network-wide synchronization [29]. Therefore, in this paper, we assume that the network is globally synchronized.

There are four components that control the proposed protocol:

- Hopping Control: This control is used to generate hopping sequences for both the slow and fast hopping interfaces. Moreover, it guarantees that the two interfaces do not share the same channel at the same time. Nodes only need to know each other's hopping sequence of the slow hopping interface.
- Discovery: New and existing nodes should periodically transmit HELLO packets over channels. The HELLO packets include the following: 1) the hopping sequence of the slow hopping interface; 2) the current time of the node; and 3) the time to switch to the next channel.
- Rendezvous: When a node has a packet, the node determines which channel the slow hopping interface of a destination node is on. Then, the node sends the packet

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through one of its two interfaces. Note that the fast hopping interface is allowed to deviate from current hopping sequence.

- Broadcast support: Broadcast packets are essential in wireless networks. For example, routing protocols maintain their routing tables or determine nodes through routing discovery based on broadcast packets. Whenever a broadcast packet needs to be transmitted, the proposed protocol transmits the broadcast packet over both interfaces. In other words, two copies of the broadcast packet are generated; one for each interface to be transmitted.

3.1 Hopping Control

The two interfaces are not allowed to share the same channel at any time, and the hopping control is used to generate hopping sequences for both interfaces. The hopping sequence of the slow interface of a node is based on a pseudo-random generator. We use a linear congruential generator (similar to [3]), which can be described by

$$X(t) = 16807 \cdot X(t-1)\, mod\, (2^{31}-1), \tag{1}$$

where $X(t)$ is the current channel number of the t^{th} sequence. $X(t)$ must be within the range of the number of channel, so $X(t)$ is modular to k, the number of channels. $X(0)$ is the seed of the hopping sequence and generated randomly.

For the fast hopping interface, the hopping control generates a deterministic hopping sequence:

$$f(t) = (f(t-1)+1)\, mod\, (k), \tag{2}$$

where $f(t)$ is the current channel of the t^{th} sequence. The hopping control does not allow both interfaces to be on the same channel. Consequently, if the sequence of the fast hopping interface is equal to the sequence of the slow hopping interface, then (2) is executed again. In other words, the fast hopping sequence jumps to another channel.

3.2 Discovery

New and existing nodes should periodically transmit HELLO packets over channels, and the nodes can receive the packets by one of the two interfaces; therefore, the nodes

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can discover each other. The HELLO packets are only transmitted through the slow hopping interfaces after they switch to new channels. Despite the fact that the HELLO packets are broadcasted, they are only transmitted through slow hopping interfaces to reduce the overhead in the network. When the nodes receive any HELLO packet through one of their interfaces, the nodes maintain records of their neighbors. These records are important for the nodes to determine their destinations.

A HELLO packet contains three fields. The first field is the seed of the slow hopping sequence of a node, and this field determines the current and future channels of the node using (1). The second field is the local clock time of the node to determine the slot hopping boundary of the node. Finally, the third field contains the remaining time to switch to the next channel. The purpose of the third field is to align the slow hopping boundary because the HELLO packet may not be transmitted immediately after switching.

3.3 Rendezvous

A node transmits only one unicast packet at any given time and uses the IEEE 802.11 MAC strategies for any transmission because we do not change the legacy IEEE 802.11 MAC protocols. Similar to parallel rendezvous multi-channel protocols, the proposed protocol allows multiple concurrent transmissions. This approach solves the congestion problem in single rendezvous multi-channel protocols [13].

The fast hopping interfaces of nodes are used for transmission, and the slow hopping interfaces of nodes are generally for reception. Therefore, if a source node has a packet to transmit, the source first determines the current channel of the slow interface of the destination node. Next, the fast hopping interface of the source switches to the same channel which the slow hopping interface of the destination is on. Finally, the packet is transmitted over the fast hopping interface according to the IEEE 802.11 MAC strategies. If the slow hopping interface of the destination is on the same channel as that of the source, the packet is transmitted through the slow hopping interface of the source.

Fig. 2 shows five channels and four nodes using the proposed protocol. During slot $i-1$, if node A has a packet for node B, but the slow hopping interface of node A is not with the same channel of the slow hopping interface of node B, node A switches its fast hopping interface to meet the slow hopping interface of node B. After that, node A uses the IEEE 802.11 MAC strategies to transmit its packet to node B through its fast hopping interface. Nodes C and D want to transmit packets to nodes D and A, respectively, during slot i. The slow hopping interfaces of nodes C and D are over Channel 5, so node C transmits its packet through its slow hopping interface. The slow hopping interface of node A, on the other hand, is on Channel 4. As a result, node D switches its fast hopping interface to Channel 4 and then transmits its packet. As a result, node D is able to transmit and receive concurrently during slot i.

3.4 Broadcast Support

Unlike the existing parallel rendezvous multi-channel protocols that have a single radio interface, the proposed protocol has two interfaces per node. When a broadcast packet needs to be transmitted, two copies of the broadcast packet are generated and passed to each interface. Then, the broadcast copies are transmitted through both interfaces, which are on two different channels. Recall that the two interfaces do not share the same channel at any time and hop according to the hopping control presented in Section 3.1. The proposed protocol schedules the next packet when both interfaces transmit their broadcast copies. Any node within the communication range of the transmitter has a high probability to receive the broadcast packet through one of the interfaces if no collisions occur.

Since different nodes are on different channels, broadcast messages may not be received by all nodes (especially when the number of channels is large). Generally, we have two possible solutions to address this issue. The first solution is to have a dedicated period on a predefined channel for broadcast packets, which it is called the broadcast channel, so the nodes turn their fast hopping interfaces on the broadcast channel during the broadcast period. Thus, all nodes transmit only their broadcast packets during the broadcast period. Another solution is by rebroadcasting. When a node receives a broadcast packet during the current slot, the node rebroadcasts the packet on a different channel in the next slot. Both solutions would degrade the network performance.

4 SYSTEM ANALYSIS

In this section, we present the system analysis of the proposed protocol. We adapt Bianchi's model [30] to analyze the throughput of our protocol because we do not change the legacy IEEE 802.11 MAC protocols.

We track only the slow hopping interface of a receiver. At each time instance, the nodes randomly select the channels for next transmissions. Similarly, we have n balls (nodes) that are thrown into k bins (channels). Thus, the number of nodes on a particular channel follows the binomial distribution [13], [31].

Following Bianchi's approach [30], all nodes have packets for transmission at all times (saturation condition), meaning that each node has a packet to transmit after each successful transmission. From [30], the transmission probability, τ, that a node transmits a packets over a channel is given

$$\tau = \frac{2(1-2p_c)}{(1-2p_c)(CW_{min}+1)+p_c CW_{min}(1-(2p_c)^m)}, \tag{3}$$

where p_c is the conditional collision probability over one channel seen by one node transmitted its packet, CW_{min} is the minimum contention window size, and m is the maximum backoff stage. The probability p_c is defined as one or more of remaining nodes transmit their packets given that one node has already transmitted its packet on the same channel so that a collision occurs over that particular channel. The probability p_c is assumed to be independent and constant and can be computed as follows:

$$\begin{aligned} p_c &= \sum_{i=1}^{n-1} \left(1-(1-\tau)^i\right) \left(\binom{n-1}{i} (\frac{1}{k})^i (1-\frac{1}{k})^{n-1-i} \right) \\ &= 1-(1-\frac{\tau}{k})^{n-1}. \end{aligned} \tag{4}$$

Note that the transmission probability τ defined in (3) is different from the transmission probability defined in Bianchi's paper because the conditional collision probability is different. τ depends on the unknown variable p_c, and Equations (3) and (4) can be solved numerically similar to [30].

P_i is defined as the probability that there is no transmission (idle) in any given time over a particular channel and given as follows:

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$$\begin{aligned} P_i &= \sum_{j=0}^{n} \left((1-\tau)^j\right) \left(\binom{n}{j}(\frac{1}{k})^j(1-\frac{1}{k})^{n-j}\right) \\ &= (1-\frac{\tau}{k})^n. \end{aligned} \tag{5}$$

Let P_s denote the probability that a successful transmission occurred over a particular channel given that at least one node transmits (i.e., exactly one station transmits over that channel). P_s is determined as follows:

$$\begin{aligned} P_s &= \frac{\sum_{j=1}^{n} \left(\binom{j}{1}\tau(1-\tau)^{j-1}\right) \left(\binom{n}{j}(\frac{1}{k})^j(1-\frac{1}{k})^{n-j}\right)}{1-P_i} \\ &= \frac{\frac{n\tau}{k}(1-\frac{\tau}{k})^{n-1}}{1-P_i}. \end{aligned} \tag{6}$$

The throughput ψ_l for channel l can be expressed as

$$\psi_l = \frac{P_s(1-P_i)E[P]}{P_i\sigma + P_s(1-P_i)T_s + (1-P_s)(1-P_i)T_c}, \tag{7}$$

where $E[P]$ is the average packet payload size, σ is the slot time, T_s is the average successful time because one node transmits over channel l successfully, and T_c is the average collision time that channel l is sensed as being busy because two or more nodes transmit their packets causing a collision. The total throughput for all channels is given

$$\Psi = \sum_{l=1}^{k} \psi_l. \tag{8}$$

Notice that (7) indicates the saturation throughput without specifying the access methods. In our protocol, we use only the RTS/CTS access mechanism, but it is very easy to apply the analytical model to the basic access method. Therefore, T_s and T_c are obtained as follows:

$$\begin{aligned} T_s &= RTS + T_{SIFS} + \delta + CTS + T_{SIFS} + \delta + H \\ &\quad + E[P] + T_{SIFS} + \delta + ACK + T_{DIFS} + \delta, \qquad (9) \\ T_c &= T_{DIFS} + RTS + T_{SIFS} + CTS + 2\delta, \qquad (10) \end{aligned}$$

where $H = PHY_{hdr} + MAC_{hdr}$ is the packet header, and δ is the propagation delay.

5 MODEL VALIDATION

In this section, we validate our analytical model presented in Section 4. The simulation platform used to validate our analysis is the ns-2 simulator (ns-2-30). We also present the performance of the IEEE 802.11 MAC protocols for comparison.

Table 1 provides the system parameters, and Fig. 3 and Fig. 4 show the saturation throughput of the proposed protocol and the IEEE 802.11 MAC protocol. The average packet payload, E[P], is 1000 bytes. The proposed protocol encounters certain overheads. Such overheads are Hello packets and switching delay for each radio interface. It can be seen that the analytical and simulation results are matched well.

As shown in Fig. 3a, when the number of channels increases, more nodes are needed to match the analytical results[2]. Fig. 4a demonstrates the throughput with different available channels and payloads, i.e., 256, 512, and 1024 bytes, when the number of nodes is 25.

To measure the improvement of the proposed protocol with respect to the IEEE 802.11 protocol, Fig. 3b and Fig. 4b show the normalized saturation throughput. We normalize the analytical throughput driven in Section 4 with the analytical throughput driven in [30] and the simulation throughput of the proposed protocol with the simulation throughput of the IEEE 802.11 MAC protocol both obtained from the ns-2 simulator [32]. As shown in Fig. 3b, the proposed protocol approximately achieves as many times as the number of channels. If the payload length is changed, the proposed protocol still achieves about k times the throughput of the IEEE 802.11 MAC scheme as shown in Fig. 4b.

Recall that the node distribution over channels follows the binomial distribution as discussed in the previous section. Fig. 5 shows two instances of the expect number of nodes over different channels for different nodes in the network. The first bar is the analytical result (the expect number of nodes over any channel is $\lfloor n/k \rfloor$, where $\lfloor . \rfloor$ is the floor operation), the second bar is the expect number of nodes over channel index 1, the third bar is the expect number of nodes over channel index 2, and so on. The last

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[2] Bianchi has stated that his model is accurate when the number of nodes is large [30]. This statement is also true in our model because our model is based on Bianchi's model.

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TABLE 1: System Parameters

Carrier sense threshold	$1.56 * 10^{-8}$ mW
Receiver sensitivity	$3.65 * 10^{-7}$ mW
Maximum transmission power (P_{max})	281.8 mW
T_{DIFS} (μs)	50
T_{SIFS} (μs)	10
PHY_{hdr} (bits)	192
Slot Time σ (μs)	20
MAC_{hdr} (bits)	272
CW_{min}	32
CW_{max}	1024
Channel bit rate	1 Mbps
ACK (bits)	112 + PHY_{hdr}
RTS (bits)	160 + PHY_{hdr}
CTS (bits)	112 + PHY_{hdr}
Hello packet (bits)	320 + PHY_{hdr}
Propagation delay δ (μs)	1
Slow hopping time (ms)	100
Fast hopping time (ms)	1
Switching delay time (μs)	100

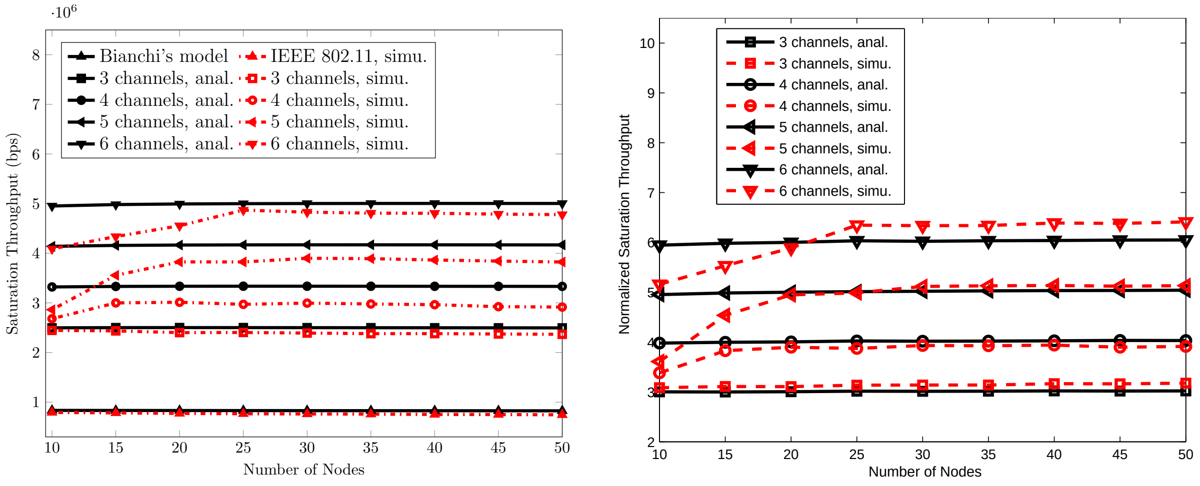
bar is the average number of nodes from all channels (i.e., the sum of expect number of nodes over channel index 1, channel index 2, $\ldots$, channel index k divided by k). From the figure, we can see the node distribution over channels is valid. Recall that we only track the slow hopping interface because the fast hopping interface of a transmitter follows the slow hopping interface of a receiver.

6 MAXIMUM SATURATION THROUGHPUT

In this section, we determine the maximum throughput, and what parameters can affect the achievable network throughput to compute the optimal transmission probability τ.

Equation (7) determines the saturation throughput analytically. By rearranging (7), we get

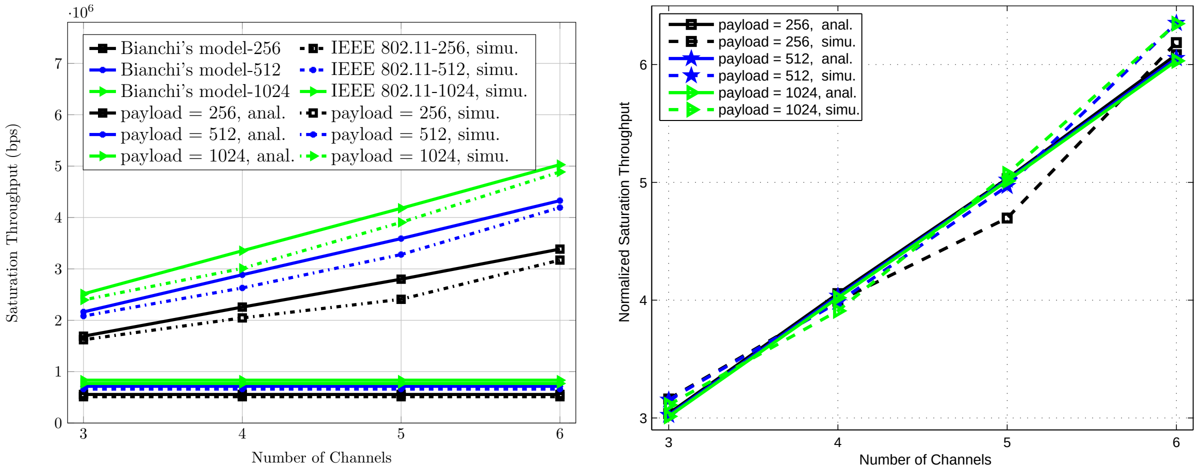
$$\psi_l = \frac{E[P]}{T_s - T_c + \frac{\sigma P_i/(1-P_i)+T_c}{P_s}} = \frac{E[P]}{T_s - T_c + \sigma y}. \tag{11}$$



(a) Throughput

(b) Normalized throughput

Fig. 3: Saturation throughput vs. different numbers of nodes and channels



(a) Throughput

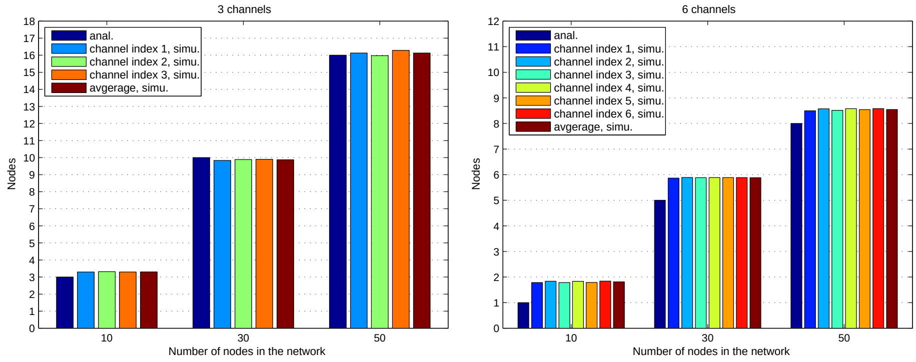
(b) Normalized throughput

Fig. 4: Saturation throughput vs. different numbers of channels and payloads.

Since $T_s, T_c, E[P]$, and σ are constants, ψ_l depends on y. When ψ_l is maximized, $1/y$ is maximized as follows:

$$\frac{1}{y} = \frac{P_s}{P_i/(1-P_i)+T_c/\sigma} = \frac{\frac{n\tau}{k}(1-\frac{\tau}{k})^{n-1}}{T_c^* - (1-\frac{\tau}{k})^n (T_c^*-1)}, \qquad (12)$$

where $T_c^* = T_c/\sigma$ is the time duration of a collision measured per σ unit. By taking the



(a) Three channels

(b) Six channels

Fig. 5: Expected number of nodes over different channels.

derivative of (12) with respect to τ and imposing it equal to 0, we obtain

$$(1-\frac{\tau}{k})^n - T_c^*\{\frac{n\tau}{k} - [1-(1-\frac{\tau}{k})^n]\} = 0. \tag{13}$$

Under the condition $\tau \ll 1$,

$$(1-\frac{\tau}{k})^n \approx 1 - \frac{n\tau}{k} + \frac{n(n-1)}{2}(\frac{\tau}{k})^2 \tag{14}$$

holds and leads to the following approximate solution:

$$\tau = k\frac{\sqrt{[n+2(n-1)(T_c^*-1)]/n}-1}{(n-1)(T_c^*-1)} \approx \frac{k}{n\sqrt{T_c^*/2}}. \tag{15}$$

Equation (13) and its approximate solution (15) indicate that the optimal transmission probability τ should consider the number of channels. In (15), within a given network, τ depends on the network size n, the number of channels k, and the system parameters m and CW_{min}. Since n and k are not a directed controllable variable, m and CW_{min} are the only way to achieve maximum throughput. This conclusion has been also stated in [30], and unfortunately, the values m and CW_{min} are fixed, as specified in the IEEE 802.11 standard.

Let $K = \sqrt{T_c^*/2}$ and use (15), from (5) and (6), we have

$$P_i = (1-\frac{\tau}{k})^n = (1-\frac{1}{nK})^n \approx e^{-1/K} \tag{16}$$

and

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$$P_s = \frac{\frac{n\tau}{k}(1-\frac{\tau}{k})^{n-1}}{1-P_i} \approx \frac{n}{(nK-1)(e^{1/K}-1)} \approx \frac{1}{K(e^{1/K}-1)}, \tag{17}$$

when n is sufficiently large. Thus, the maximum achievable throughput ψ_l^{max} of channel l can be approximated as

$$\psi_l^{max} = \frac{E[p]}{T_s + \sigma K + T_c(K(e^{1/K}-1)-1)}, \tag{18}$$

which is independent of n and k, and the maximum achievable throughput of all channels is the summation of the maximum throughput of each channel and given

$$\Psi^{max} = \sum_{l=1}^{k} \psi_l^{max}, \tag{19}$$

which depends on the number of channels in the network, but not the number of nodes. To determine the improvement of the proposed protocol, the improvement gain $\wp$ can be determined

$$\wp = \frac{\Psi^{max}}{S_{max}} = k, \tag{20}$$

where S_{max} is the maximum achievable throughput of single-channel networks obtained in [30].

7 SATURATION THROUGHPUT LIMIT

In the previous section, we determine the maximum achievable throughput, and how the system parameters and network topology (i.e., the number of stations and channels) affect the maximum throughput. In this section, we compute the throughput limit when we have a large number of channels, i.e., $k \to \infty$, to investigate the performance bottleneck of the proposed protocol.

Assume the number of channels is large ($k \to \infty$) for a fixed number of nodes n, the question is what is the upper limit throughput that we can achieve? The following remarks summarize the results:

Remark 1. When the number of channels is large ($k \to \infty$), from (3), the transmission probability τ is only depends on the minimum window size (no exponential backoff)

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$$\tau = \frac{2}{CW_{min}+1}. \tag{21}$$

Remark 2. From (8), the total throughput of all channels is given by

$$\begin{aligned}\Psi &= \lim_{k\to\infty} \frac{kP_s(1-P_i)E[P]}{P_i\sigma + P_s(1-P_i)T_s + (1-P_s)(1-P_i)T_c} \\ &= \frac{n\tau E[P]}{\sigma} = \frac{2nE[P]}{(CW_{min}+1)\sigma}. \end{aligned} \tag{22}$$

Equation (22) proves that the proposed protocol does not have any bottleneck issue.

Remark 3. A special case is when the number of channels is equal to the number of nodes ($k = n$), and n goes to infinity. Under the condition $\tau \ll 1$, p_c from (4) can be derived by

$$p_c = 1 - e^{-\tau} \approx 0. \tag{23}$$

From (7), We can obtain the throughput of a given channel

$$\psi = \frac{\tau e^{-\tau}E[P]}{\sigma e^{-\tau} + \tau e^{-\tau}T_s + (1 - e^{-\tau} - \tau e^{-\tau})T_c} \approx \frac{\tau E[P]}{\sigma + \tau(T_s - T_c)}. \tag{24}$$

8 SIMULATION RESULTS

In this section, simulation results are given to first compare the proposed protocol with McMAC [3] in single-hop networks. Recall that both DSP and McMAC follow the parallel rendezvous approach, but DSP employs two interfaces (one of the two interfaces follows slow hopping and never deviates from its hopping sequence) and McMAC uses one interface that can deviate from its default hopping sequence, thereby leading to the busy receiver problem. This comparison is useful for investigating performance gain of additional interface used in the DSP.

Then, we evaluate the proposed DSP in multi-hop networks and finally compare it with the HMCP [12]. The Dynamic Source Routing (DSR) protocol is adopted [33] in multi-hop networks. Recall that both DSP and HMCP have two radio interfaces, but

DSP employs channel hopping for both interfaces and HMCP has one interface fixed and the other interface switchable.

We select the following three performance metrics:

1) *Average aggregate throughput*. To achieve k times the throughput of a single-channel network, one may say that each node should have k interfaces, which is unpractical. In single-hop networks (Sections 4 and 5), we show that the proposed protocol approximately achieves k times the throughput of IEEE 802.11 single channel MAC protocol with only two interfaces per node. In multi-hop networks, the proposed protocol utilizes all channels by frequency hopping and achieves about k times the capacity of the IEEE 802.11 MAC protocol as discussed in the following.
2) *Average end-to-end packet delay*. The end-to-end packet delay is important for real time applications, and it is the time duration for a packet to be received correctly by its destination. The delay occurs because of queueing, backoff, propagation, access, switching, and transmission times. The MAC queueing size of each node is 50 packets, and packets will be dropped after reaching a retry limit, i.e., 7. We do not take into account the dropped packets.
3) *Normalized routing overhead*. Most routing protocols use broadcast information to determine a routing path from any source node to any destination node. In the proposed protocol, nodes could be over different channels and thereby affecting the routing protocols. In addition, any broadcast packet is transmitted through two interfaces. The normalized routing overhead is the total transmitted routing packets normalized by the total received packets. For any routing packet sent over multiple hops, we count each hop as two using the proposed protocol and as one using the IEEE 802.11 MAC scheme. At the same time, we only count the received packets at destination nodes.

8.1 Simulation Settings

The ns-2 simulator (ns-2.30) [32] is used for simulations, and the simulation parameters are presented in Table 1. In addition, in multi-hop networks, the retry limit is set to 7, i.e., after 7 retransmissions of a packet without succeeding, the packet is dropped and the next packet in the queue is scheduled for the next transmission. The two-ray

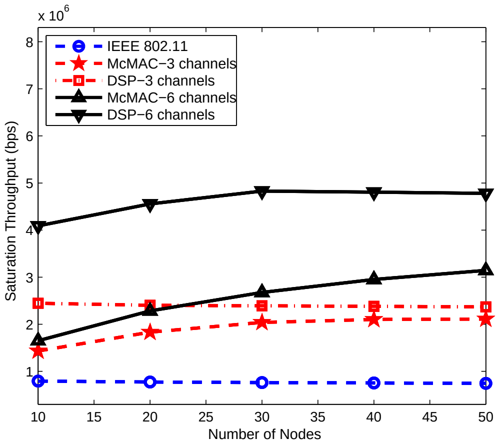

Fig. 6: Comparison between DSP and McMAC.

path loss model is adopted in the simulations, and the radio transmission range and the carrier sensing range of each node of each channel is 250 meters and 550 meters, respectively.

We simulate multi-hop wireless networks by randomly deploying 100 mobile nodes into two different network sizes: $250m$x$250m$ and $500m$x$500m$ square areas. We refer to the $250m$x$250m$ square area as the dense network and the $500m$x$500m$ square area as the sparse network. A node movement is simulated using the random waypoint model [34] with speed uniformly distributed in the range [0, 20] m/s, and the simulation results are shown with five different pause times: 60, 120, 300, 600, and 900 seconds. The simulation time is 900 seconds, so a pause of 900, the length of the simulation time, means no mobility. Each simulation scenario is run for five different movement patterns. Thus, we have a total of 50 different scenarios.

There are 50 flows with rate of 500 Kbps in the simulations, and source and destination pairs are randomly chosen. Each traffic flow in the network uses the constant bit rate (CBR) traffic model, and the packet size is 1024 bytes. We assume the switching delay time is 100 μs. Existing wireless interfaces can switch between channels with a delay of 130 μs [27], and it is expected that the channel switching delay of wireless interfaces will be reduced to 40-80 μs [4], [13].

8.2 Simulation Results

We first present the saturation throughput between the DSP and McMAC protocols in single-hop networks as shown in Fig. 6. The simulation parameters are presented in Table 1 with packet size of 1000 bytes, and, for McMAC, we set $P_{deviate}$ to 0.1. From the figure, DSP preforms better than McMAC because the proposed DSP avoids the busy receiver problem and utilizes both interfaces on different channels for transmission and reception at any time (i.e., a node can work as a full-duplex system on different channels). In addition, McMAC suffers more from the busy receiver problem when the number of channels increases.

Fig. 7 and Fig. 8 show the performance of the proposed DSP in multi-hop environments. DSP-3, DSP-6, and DSP-12 mean that the proposed DSP has 3, 6, and 12 channels, respectively. Fig. 7a shows the average aggregate throughput of the dense network. The throughput of DSP is higher than the throughput of IEEE 802.11, and the two protocols achieve steady throughput values with different mobility patterns because the size of the network is small. To examine the achievement of the proposed protocol, the proposed DSP achieves 3.63, 9.57, and 20.88 times the throughput of the IEEE 802.11 MAC protocol for 3, 6, and 12 channels, respectively, when there is no mobility, i.e., the pause time is 900 seconds. These achievements are due to k available channels and channel reuse.

Fig. 7b presents the average end-to-end delays of the dense network. The proposed DSP achieves less delay with more channels. The uncertainty of the delay using the IEEE 802.11 strategies is high because the network has only a single channel and all nodes compete over the shared channel.

Since our proposed protocol transmits any broadcast packet through two interfaces, this approach increases the likelihood of discovering neighboring nodes and determines shorter routing paths, but increases routing messages. In Fig. 7c, we show the normalized routing overhead and observe that the proposed protocol encounters less normalized routing overhead with more available channels due to better network performance and resolving the congestion.

In Fig. 8a, the throughput of the protocols increases and then decreases due to the mobility patterns and spatial reuse [35]. However, the proposed DSP provides better performance, and the more channels the network has, the better performance will be. When there is no mobility, for instance, the proposed DSP achieves 2.99, 6.37, and 12.33 times the throughput of the IEEE 802.11 MAC protocol for 3, 6, and 12 channels, respectively. When the pause time is 300 seconds, the proposed DSP achieves 3.22, 7.05, and 14.12 times the throughput of the IEEE 802.11 MAC protocol for 3, 6, and 12 channels, respectively. Thus, the capacity of the proposed MCMAC protocol approximately achieves k (the total number of channels in the network) times the capacity of the IEEE 802.11 MAC protocol.

In Fig. 8b, the end-to-end delay of the IEEE 802.11 MAC strategies encounter higher delay than the proposed DSP because the IEEE 802.11 MAC protocols use a single channel. Comparing the dense network as shown in Fig. 7b with the sparse network as shown in Fig. 8b, the delay differences of the DSP between the sparse and dense networks are small, but the delay differences of the IEEE 802.11 MAC protocol are high.

Fig. 8c shows the normalized routing overhead in the sparse network. The IEEE 802.11 incurs high routing overhead when the mobile nodes are in fast mobility. However, when there is less or no mobility, the IEEE 802.11 protocol has the same routing overhead ratio as the proposed DSP with three channels. As the number of channel increases, the routing overhead of DSP has less effect.

Finally, we compare the DSP with the HMCP in the multi-hop networks and focus only on the aggregate throughput. In Fig. 9, we show the throughput of the dense network for five different scenarios and the last bar is the average (i.e., Fig. 9a shows the throughput when the mobile nodes pause every 300 seconds and Fig. 9b presents the throughput when no mobility). From the figures, it shows that in some scenarios DSP achieves better throughput than HMCP (e.g., scenarios 3 and 4 in Fig. 9a) because HMCP suffers from unbalanced traffic load over channels discussed in Section 1 while in other scenarios HMCP achieves slightly higher throughput than DSP due to the two main reasons: 1) HMCP does not suffer from unbalanced traffic load; and 2) DSP has an overhead from the switching delay of the slow hopping interfaces. Thus, the throughput of HMCP varies according to the traffic pattern, but the throughput of DSP is steady.

In Fig. 10, we further compare the performance of DSP with HMCP in five different scenarios and their averages in the sparse network when there is no mobility (there are three and six available channels as shown in Fig. 10a and Fig. 10b, respectively). The observations from Fig. 10 are the same as that in Fig. 9. Note that when the number of channels is large, the performance of DSP can be enhanced because of the spatial channel reuse (i.e., reducing the interference). For example, there is difference between the throughput for scenario 5 in Fig. 9b and Fig. 10b when there is no mobility. In the first case, there are only three channels in the dense network, and, in the second case, the number of channels has increased to six in the sparse network.

9 CONCLUSION AND FUTURE RESEARCH

In this paper, we have proposed a novel MCMAC protocol based on the fast and slow hopping approaches. Our protocol does not change the legacy IEEE 802.11 MAC strategies and employs two radio interfaces per node. The fast hopping interface is mainly for transmission, whereas the slow hopping interface is for reception. In particular, whenever a transmitter has a packet for a receiver, the fast hopping interface of the transmitter follows the slow hopping interface of the receiver. The proposed protocol is based on the multiple rendezvous approach and avoids the busy receiver problem because the slow hopping interface never deviates from its hopping sequence. In addition, an analytical study has been presented to evaluate the network throughput. Simulation results have been provided to validate the analytical model and to demonstrate the improvement in the capacity of the network. In addition, the upper throughput limit is computed in the context of an infinite number of channels. In our future work, we will address the energy consumption issue and develop a eco-friendly protocol.

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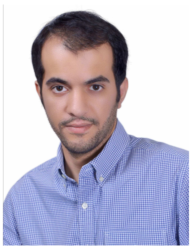

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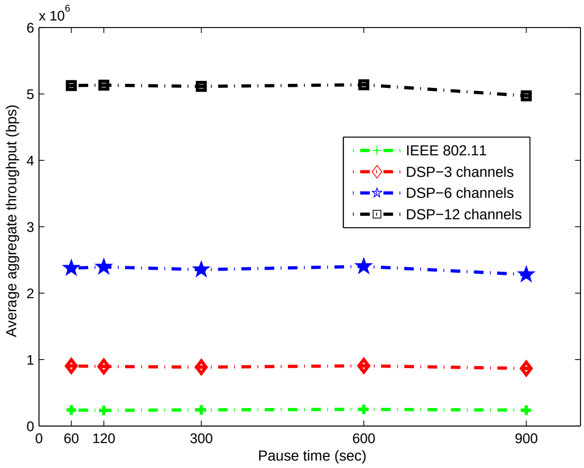
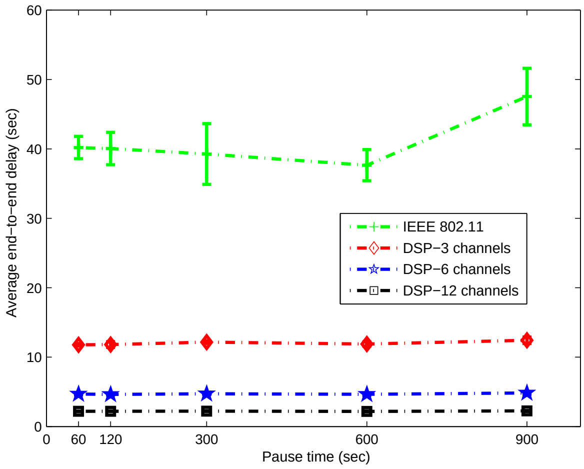
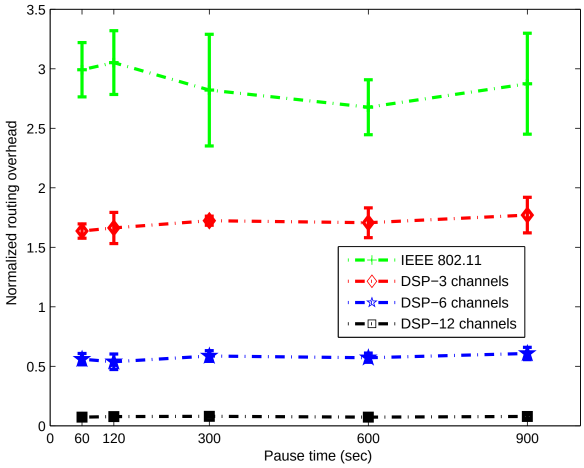


(a) average throughput

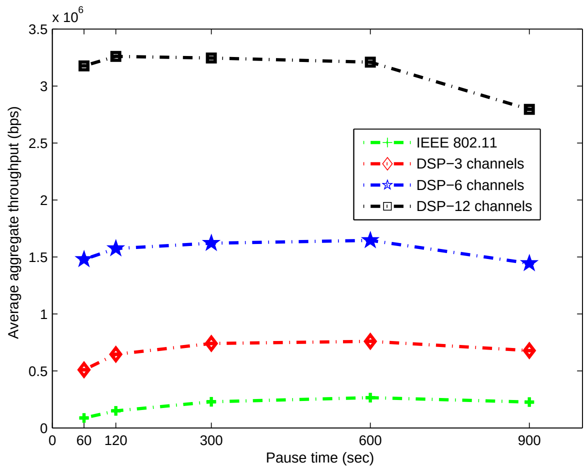


(b) average end-to-end delay

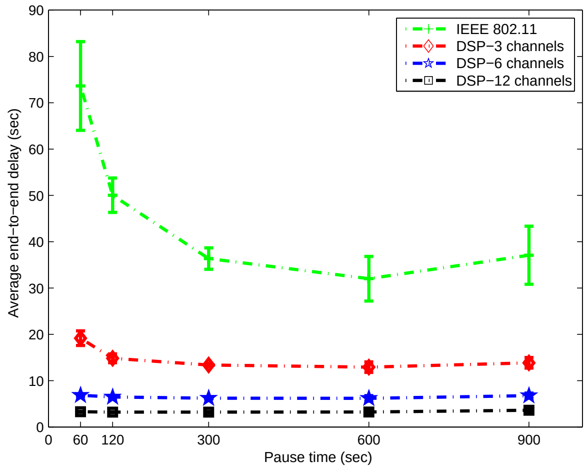


(c) normalized routing overhead

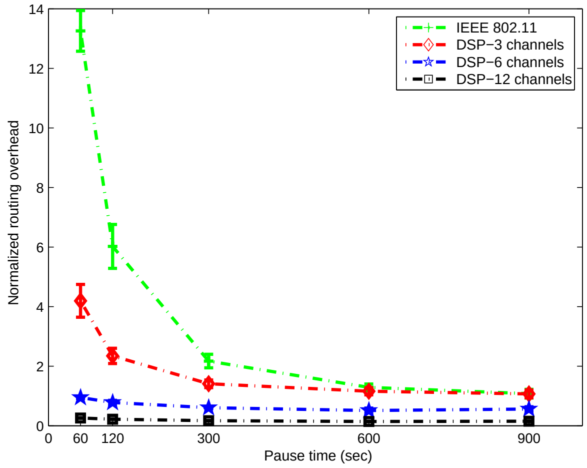
Fig. 7: The performance of the dense network.



(a) average throughput

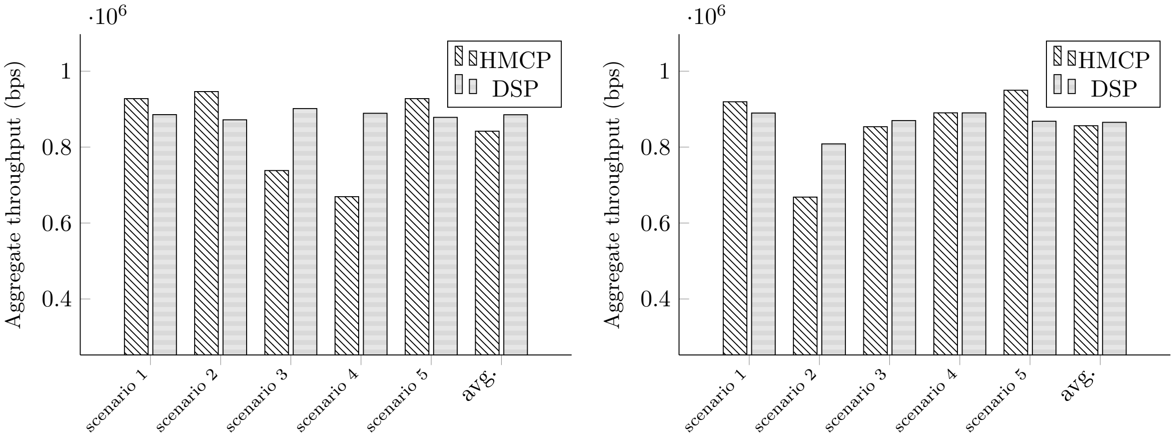


(b) average end-to-end delay



(c) normalized routing overhead

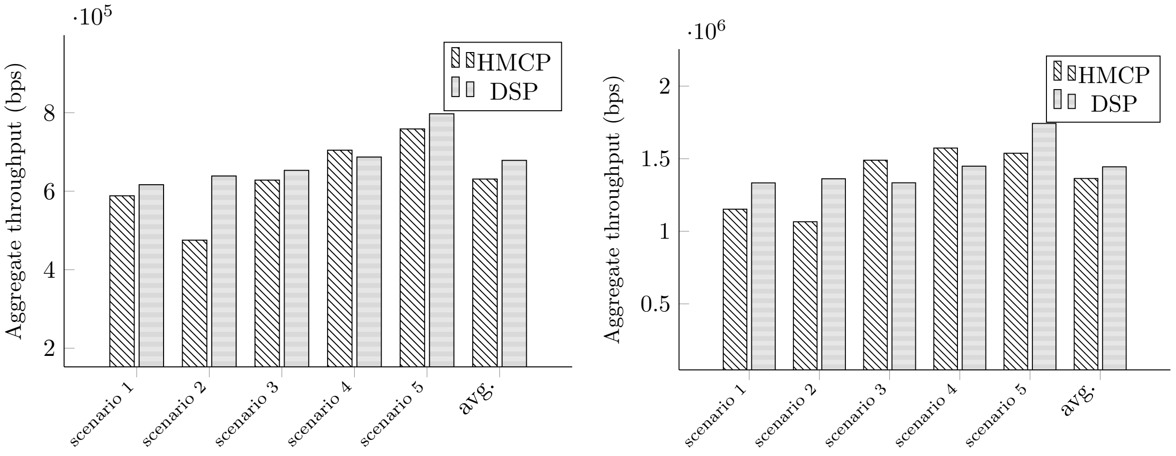
Fig. 8: The performance of the sparse network.



(a) pause of 300 sec.

(b) pause of 900 sec.

Fig. 9: Comparison between DSP and HMCP [12] when three channels available in the dense network.



(a) Three channels

(b) Six channels

Fig. 10: Comparison between DSP and HMCP [12] when no mobility in the sparse network.