Multi-Channel Assignmentment for Heterogeneous Wireless Mesh Networks

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***Abstract*—Multi-channel assignment schemes have recently been proposed to improve the network throughput of multi-hop wireless mesh networks (WMNs). In these schemes, channel coordination is done either through time synchronization across all the nodes, or through the use of a dedicated channel for the transmission of necessary control messages. Either way, excessive system overhead or waste of bandwidth resource becomes inevitable and undermines the overall network throughput. To resolve these problems, we consider the heterogeneity in large-scale networks and propose a synchronization-free, hybrid temporal-spatial multi-channel assignment scheme. The gateway is allowed to switch its radios to all the available channels sequentially in a round-robin fashion. This temporal channel assignment approach ensures that all the neighboring nodes that communicate with the gateway directly shall have a fair access to the gateway. The channel assignment for the remaining wireless nodes is based on the geographical location and channel/radio availability (a spatial approach) to avoid the interface during the transmission period. Simulation results demonstrate that our proposed scheme can improve the network throughput substantially with the acceptable collision ratio.**

Keywords-wireless mesh networks (WMNs); multi-channel; throughput; temporal; spatial; heterogeneous

I. INTRODUCTION

To meet the increasing demand for better and seamless network services, wireless mesh networks (WMNs) have emerged and attracted more attention recently [1]. Considering the limited radio transmission range, each node has to utilize other nodes to communicate with gateway in distance through multi-hop communications. When the number of communication hops traversed increases, it tends to degrade the network performance sharply mainly due to the increased number of contending transmissions [2].

In conventional single-channel networks, if the medium is busy nodes must defer their transmissions until it becomes idle again. Only after sensing the channel becoming idle, a node may try to reserve the channel and start transmitting its packets. Fortunately, the IEEE 802.11b/802.11g and IEEE 802.11a standards provide 3 and 12 orthogonal (non-overlapping) channels respectively, which could be used simultaneously within a neighborhood to improve the network throughput. So *et al.* proposed a multi-channel MAC (MMAC) protocol which requires only one radio per node [3]. In the MMAC protocol, the beacon interval is divided into cycles composed of two phases: control phase and data exchange phase. In the control phase, all nodes listen to a predefined, common channel to negotiate a channel to be used during the data exchanged phase. Since this protocol needs global fine-grained time synchronization among nodes in the control phase, it is infeasible to be applied to a WMN with a large number of nodes without modifying 802.11 MAC. Wu *et al.* proposed a dynamic channel assignment (DCA) scheme in an on-demand style, which maintains a dedicated channel for control messages and other channels for data packets [4]. However, this scheme wastes the valuable system resources, especially when the number of available channels is limited. Given multi-radio per node, the joint multi-channel multi-radio assignment and routing problem is investigated recently [2,5-7]. Although these solutions are amenable to implementation with legacy hardware, these static approaches are not adapted to the case of instantaneous, variable, and dynamic traffic load demand.

To address the aforementioned challenges, we extend our previous work [8] to study a joint multi-channel assignment and routing problem in a heterogeneous multi-hop WMN where each node is equipped with the various numbers of radios. Basically, the proposed scheme has the following characteristics:

- Control messages and data packets can be transmitted in different channels separately, which increases the limited channel bandwidth utilization and saves the valuable system resources;
- Multiple orthogonal channels are assigned to the communication nodes instead of packet routes/flows. That is, the communication node only needs to find the next hop node for its transmission, which decreases the algorithm complexity;
- Gateway utilizes available channels fairly by assigning its radios to the different channels sequentially in a round-robin fashion to collect the packets from its neighbors, which is considered the *temporal* property of the proposed scheme;
- Other nodes simultaneously utilize different orthogonal channels within their neighborhoods for the communication, which is considered the *spatial* property of the proposed scheme.

II. PROBLEM FORMULATION

In this paper, we assume all nodes over the network are actively associated with only one gateway. Other assumptions include:

(1) The protocol interference model is used. In this model, a transmission on channel i over some link is successful when all potential interferers in the neighborhood of the sender and the receiver are silent on channel i for the duration of this transmission;

(2) The distribution of the nodes is random. Each non-gateway node has the limited memory size and may function

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as a source node which generates data packets. The memory size of the gateway is assumed to be unlimited;

(3) All nodes maintain their own clocks independently.

Table I lists the notations used in this paper.

TABLE I. SYMBOLS

Symbol	Description
V	set of all nodes over the network
S_C	set of orthogonal channels, denoted as channel 1, 2,…, $\|S_C\|$
G	undirected bilateral graph
$S_N(u)$	set of neighbors of node u in G
$S_{AC}(u)$	current assigned channel set of node u
$S_{WC}(u)$	current working channel set of node u
$C(i)$	capacity of channel i, $i \in S_C$
$\kappa(u)$	number of radios of node u
$M(u)$	total memory size of a non-gateway node u
$M_a(u)$	current available memory size of a non-gateway node u
r_u	radio transmission range of node u
$H(u)$	hop count of node u

Definition 1. A network can be modeled by an undirected, bilateral graph $G=(V, E)$. Given a node u and a node v, $(u, v) \in E$ if and only if $r_u \geq \mathrm{dis}(u,v)$ and $r_v \geq \mathrm{dis}(u,v)$ where $\mathrm{dis}(u,v)$ is the Euclidean distance between node u and node v. Obviously, $v \in S_N(u)$ if and only if $u \in S_N(v)$. Therefore, for direct communication, two nodes need to be within *radio range* of each other, and need to have at least one common channel assigned to their radios.

Definition 2. The hop count of node u is h if the least number of hops traversed by a packet between u and the gateway is h in graph G. The gateway is called 0-hop node.

Graph G can be formed by exchanging HELLO message. Each node u can obtain its hop count $H(u)$, maintain the neighbor set $S_N(u)$ and the number of radios of its neighbors. Then, each node u randomly assigns $\kappa(u)$ channels from S_C to its radios as its assigned channel set $S_{AC}(u)$, where $|S_{AC}(u)|=\kappa(u)$.

The multi-channel assignment problem for heterogeneous WMN is described as follows:

Given-Orthogonal channel set S_C and an undirected, bilateral graph G that consists of a gateway and a number of heterogeneous wireless nodes;

Objective-Assign the available channels to the radios of senders (including the source nodes and the forwarding nodes on the routing paths from the source nodes to the gateway) and route the traffic between the source nodes and the gateway for a given time period, in such a way that the throughput of the WMN is maximized.

Constraints:

(1) For each node u, it can utilize at most $\kappa(u)$ distinct channels simultaneously for communication;

(2) The proposed scheme should not require global time synchronization;

(3) There is less interference within the communication region of each sender in its transmission time period.

III. MULTI-CHANNEL ASSIGNMENT SCHEME

We extend the Hybrid Temporal-Spatial Multi-channel Assignment (HTSMA) scheme [8] here for the general case where each node is equipped with various numbers of radios. The HTSMA scheme consists of two parts, the channel assignment scheme for a h-hop node ($h\geq 1$) and the channel assignment scheme for the gateway, which are described in section III.A and section III.B, respectively.

Spatial algorithm (*u*: node id)

// process for the h-hop sender u (h≥1)

1. **if** $H(u)$ is 1 // node u is a 1-hop node
2. Keep staying on the current assigned channel set $S_{AC}(u)$
3. **return**
4. $S_{C\_avail}=S_C \setminus (\bigcup_i u.\mathrm{CUT}[i].\mathrm{TRS.NWC})$
5. **if**(S_{C_avail} is Φ **or** $|S_{WC}(u)|$ is $\kappa(u)$ **or** ($\forall i$, $|u.\mathrm{CUT}[i].\mathrm{TRS}|$ is $u.\mathrm{CUT}[i].\mathrm{NRN}$))
6. $j \leftarrow \arg min\{u.\mathrm{CUT}[x].\mathrm{TRS.CBT} + u.\mathrm{CUT}[x].\mathrm{TRS.ADP}\}$
7. Sleep ($u.\mathrm{CUT}[j].\mathrm{TRS.CBT} + u.\mathrm{CUT}[j].\mathrm{TRS.ADP} - t$)
8. **goto** line 4
9. **else** $S_T(u) \leftarrow \{i \mid i \in S_{C\_avail}\}$ s.t. $|S_T(u)|$ is $min\{\kappa(u)-|S_{WC}(u)|, |S_{C\_avail}|\}$
10. $S_{T'}(u) \leftarrow \{j \mid j \in S_{AC}(u) \setminus S_{WC}(u)\}$ such that $|S_{T'}(u)| == |S_T(u)|$
11. $S_{AC}(u) \leftarrow S_{WC}(u) \bigcup S_T(u) \bigcup (S_{AC}(u) \setminus (S_{WC}(u) \bigcup S_{T'}(u)))$
12. Assign the channels within the set $S_T(u)$ to the idle radios of node u
13. Broadcast the Request-To-Transmit (RTT) messages on set $S_T(u)$, piggybacking value $M(u)-M_a(u)$
14. Initialize timer T_{neg} for each channel that broadcasts RTT message
15. **while** (current clock time $t_{\mathrm{cur}}<T_{\mathrm{neg}}$)
16. { **if** (node u receives a Request-To-Reply (RTR) message from a node v on channel $k \in S_T(u)$)
17. Cancel the timer T_{neg} on channel set $S_T(u)$
18. Broadcast a Channel-REserve (CRE) message on channel set $S_C \setminus S_{WC}(u)$, piggybacking channel k, beginning time and announced duration period ($=min\{M(u)-M_a(u), M_a(v)\}/C(k)$)
19. $S_{WC}(u) \leftarrow S_{WC}(u) \bigcup \{k\}$ and transmit data to node v on channel k
20. **return** }
21. **goto** line 4

// process for the h-hop receiver u (h≥1)

22. **if** (node u receives a RTT message from a node m on channel l)
23. **if** ($m \in S_N(u)$ **and** $|S_{WC}(u)|<\kappa(u)$ **and** ($\forall m$, .CUT[m].TRS.NWC$\neq l$) **and** $M_a(u)!=0$)
24. $T(u) \leftarrow T_{\mathrm{neg}}[\alpha(1-M_a(u)/M(u))+\beta \dfrac{|S_{WC}(u)|/\kappa(u)}{\sum_{v\in S_N(u)\bigcup\{u\}} |S_{WC}(v)|/\kappa(v)} + (1-\alpha-\beta)\, H(u)/H_{\max}]$
25. Initialize a timer $T(u)$
26. **while** (current clock timer $t_{\mathrm{cur}}<T(u)$)
27. { **if** (u receives a RTR message or a CRE message M_w from w on channel l **and** $w \in S_N(u)$)
28. Cancel the timer $T(u)$
29. Insert a record (w, $\kappa(w)$, (l, M_w.CBT, M_w.ADP) into its CUT }
30. Broadcast a RTR message on channel set $S_C \setminus S_{WC}(u)$, piggybacking channel l, begining time, its available memory size $M_a(u)$ and announced duration period ($=min\{M(m)-M_a(m), M_a(u)\}/C(l)$)
31. $S_{WC}(u) \leftarrow S_{WC}(u) \bigcup \{l\}$
32. **if** (node u receives a RTR message or a CRE message M_p from a node p on its idle radio **and** $p \in S_N(u)$)
33. Insert a record (p, $\kappa(p)$, (M_p.NWC, M_p.CBT, M_p.ADP) into its CUT

Figure 1. Pseudo-code for a h-hop node ($h\geq 1$).

A. *h-hop (h≥1) node: a spatial channel assignment scheme*

Based on graph G, each non-gateway node can maintain a local channel utilization table (CUT) dynamically. Each entry in this table is composed of three fields: the node ID (NID); the number of radios of this node (NRN); and the triple set (TRS) including the numbered working channel (NWC) by this node, the communication beginning time (CBT), and the announced duration period (ADP) on this occupied channel. Each sender needs to check the CUT to find an appropriate channel, and assign such a channel to the idle radio of sender and receiver before the transmission. The detailed algorithm performed at any h-hop node at the moment t is presented in Fig. 1.

Fig. 2 illustrates a simple scenario including five nodes. Each node, say node u, is labeled with the number of radios $\kappa(u)$, the assigned channel set $S_{AC}(u)$, the current working channel set $S_{WC}(u)$, the memory size $M(u)$, current available memory size $M_a(u)$, and the hop count $H(u)$. In Fig. 2 (a), we observe that 4-hop node A is communicating with 3-hop node C on channel 3, and 4-hop node B is communicating with 5-hop node E on channel 6 at time t. Let us assume that the sender A has extra packets to send. Since $\kappa(A)$=2 and $S_{WC}(A)$={3}, only a single channel (for example channel 1) can to be selected randomly. Then node A broadcasts a RTT message on channel 1, piggybacking the value $M(A)$-$M_a(A)$ (=10 packets). Besides, the timer T_{neg} is initialized. All neighbors that have the idle radio on channel 1 (node B and node D in this case) will receive this RTT message and initialize their local timers independently.

Given $|S_C|$=6, $C(1)$=1Kbps, $H_{\max}$=10, α=0.3 and β=0.4, we have $T(B)$=0.46T_{neg} and $T(D)$=0.312T_{neg}. Since node D has the smaller timer than node B, node D will become a receiver and broadcast a RTR message to establish the communication with node A. The duration period of data communication is $min\{M(A)\text{-}M_a(A),M_a(D)\}/C(1)$ (=8 ms).

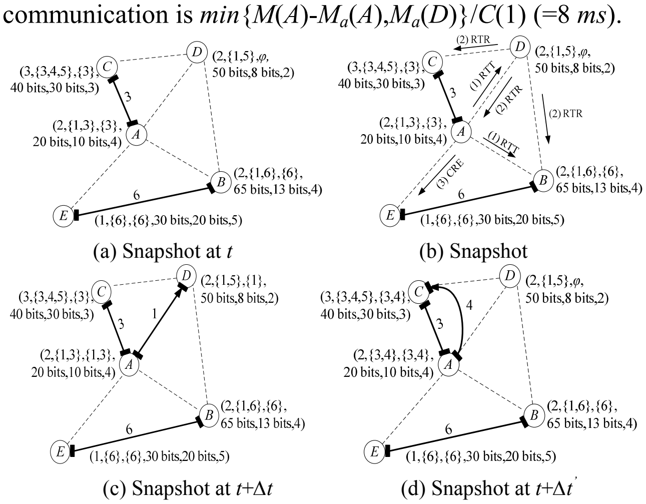


Figure 2. An illustrated example for some h-hop nodes (h≥2).

Note when node B overhears a RTR message from node D (on channel 1 in this case), then node B will insert a record of node D about channel 1 utilization information into its CUT, which prohibits node B from using channel 1 unless node D finishes the communication (with node A). Once receiving the RTR message, node A will reserve channel 1 for transmission by broadcasting CRE message on all channels. The purpose of CRE (or RTR) message is to notify all neighbors of node A (or node D) that node A (or node D) has found an available receiver (or sender) on channel 1. Correspondingly, all other neighbors of node A, i.e., node C and node E, will insert the information regarding the communication between node A and node D on channel 1 into their CUTs. The control message flow and the channel assignment snapshot are shown in Fig. 2(b) and (c), respectively. Similarly, when channel 4 (instead of channel 1) is selected randomly by node A at the moment t, only node C will be the exclusive receiver. In this case, the channel assignment snapshot is shown in Fig. 2(d).

```
Temporal algorithm (u: node id)
// process for the gateway node u
1.  N_SC←N_SC+κ(GW)      // initial value of N_SC is 0
2.  C_switch←max{i|i∈S_AC(u)}+1 mod |S_C|
3.  Broadcast a Request-To-ReceiVe (RTRV) message on channel
    j∈S_AC(u)
4.  Initialize a timer T_neg for each channel j∈S_AC(u)
5.  while (current clock time t_cur<T_neg)
6.  { if (node u receives a REPLY message on channel j)
7.        Cancel the timer T_neg
8.        Broadcast a RESerVe (RESV) message on channel j
9.        Initialize a timer T_c //T_c is used for channel fair utilization
10.       while (current clock time t_cur<T_c)
11.       {  if (node u receives a END message)
12.              Cancel the timer T_c
13.              S_AC(u)←S_AC(u)∪{C_switch}\{j}
14.              Switch to channel C_switch and goto line 3 }
15.       Broadcast a STOP message on channel j
16.       S_AC(u)←S_AC(u)∪{C_switch}\{j}
17.       Switch to channel C_switch and goto line 3   }
18.   S_AC(u)←{x| x=y+1,…, y+κ(GW) mod S_C where y=max{z| z∈S_AC(u)}}
19.   Switch all radios to channel set S_AC(u)
20.   goto line 1
// process for the 1-hop node u
21. if (node u receives a RTRV message on channel k)
22. if (|S_WC(u)|<κ(u) and (∀m, u.CUT[m].TRS.NWC≠k) and M_a(u)<M(u))
23.      N_t(u)←number of transmissions between node u and gateway
         before current moment t
24.      T_k(u)←T_neg[δM_a(u)/M(u)+(1−δ)N_t(u)/N_SC]
25.      Initialize the timer T_k(u)
26.      while (current clock time t_cur<T_k(u))
27.      { if (node u receives a RESV message on channel k)
28.            Cancel the timer T_k(u)
29.            return    }
30.      Broadcast a REPLY message and mark itself as a sender node
31. if (node u receives a RESV message on channel l and node u is a
    sender)
32.      N_t(u)←N_t(u)+1
33.      Transmit the data to the gateway on channel l
34.      Broadcast a END message //cease the communication proactively
35. if (node u receives a STOP message on channel m and node u is a
    sender)
36.      Stop data transmission on channel m
```

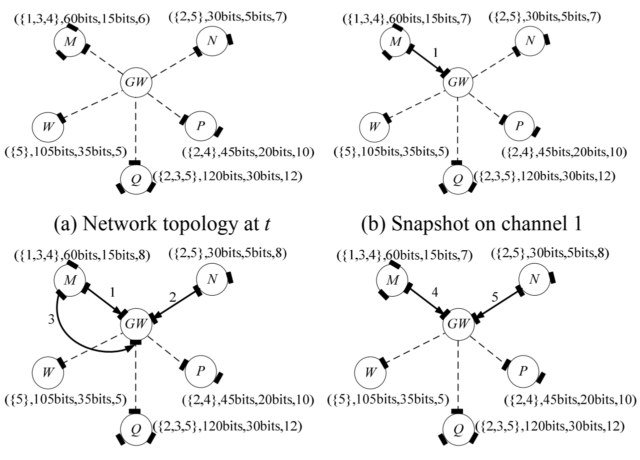
Figure 3. Pseudo-code for the gateway and 1-hop node.

With the spare radios, the node (say node B, C or D in our case) are still allowed to communicate on another available channel during the current data communication period. By this way, the efficiency of channel utilization is enhanced. Therefore, for each node, data packets are communicated concurrently through different channels on different radios to exploit parallelism.

B. Gateway: a temporal channel assignment scheme

Given the number of radios of the gateway $\kappa(GW)$, in order to utilize each channel and receive the packets from each 1-hop node in the multi-channel scenario, the gateway should switch the assigned channels in the channel set circularly. For fairness purpose, the original working interval of each channel is set to be equal, denoted as T_c. The detailed algorithm performed at the gateway (or a 1-hop node) at the moment t is presented in Fig. 3.

Fig. 4 illustrates an example with five 1-hop nodes and a gateway. As shown in Fig. 4(a), each 1-hop node, say node P, is labeled with the assigned channel set, the memory size $M(P)$, the current available memory size $M_a(P)$, and the number of transmissions as a sender node $N_t(P)$. Given S_C={1,2,3,4,5}, $\kappa(GW)$=3 and $S_{AC}(GW)$={1,2,3} at the moment t, then we have C_{switch}=4 (shown in line 2 of Fig. 3). Then the gateway broadcasts the RTRV messages on channels 1~3, respectively. Meanwhile, the timers T_{neg} is also initialized for each channel.



(a) Network topology at t (b) Snapshot on channel 1

(c) Complete snapshot (d) Complete snapshot

Figure 4. An illustrated example with a gateway and five 1-hop nodes.

Once the 1-hop node (node M in this case) receives the RTRV message on channel 1, it will defer broadcasting a REPLY message to compete for the access medium after a back-off time $T_1(M)$. When the gateway receives a REPLY message before T_{neg} expires, it will broadcast a RESV message to prohibit the transmission from other 1-hop nodes that stay on channel 1, as well as initializing a timer T_c to limit the excessive utilization duration of channel 1. When the 1-hop sender M receives the RESV message, it begins transmitting its data packets to the gateway on channel 1, as shown in Fig. 4(b). The value of $N_t(M)$ is also increased by 1. If node M finishes the data transmission before the timer T_c expires, it will disconnect the data communication proactively by broadcasting an END message.

On receiving this message, the gateway will switch to the next idle channel C_{switch} (channel 4 in this case) immediately. If node M does not finish the data transmission after the timer T_c expires (i.e., the gateway has not received END message after the timer T_c expires), the gateway will disconnect the data communication proactively by broadcasting a STOP message and switch to channel 4 immediately. After the sender M receives this message, it will stop transmitting. On the other hand, node N, P or Q has the chance to access channel 2, which depends on the value of line 24 of Fig. 3. When N_{SC}=60 and δ=0.3, we have $T(N)=0.132T_{\text{neg}}$, $T(P)=0.25T_{\text{neg}}$ and $T(Q)=0.215T_{\text{neg}}$, which means that node N can be a sender on channel 2. Similarly, given δ=0.3, we have $T(M)=0.145T_{\text{neg}}$ and $T(Q)=0.215T_{\text{neg}}$, which means that node M can be a sender on channel 3. Therefore, given δ=0.3, the complete channel assignment snapshot is shown in Fig. 4(c).

Given $S_{AC}(GW)$={4,5,6}, N_{SC}=60 and δ=0.3 at time t, with the network topology shown in Fig. 4(a), the complete channel assignment snapshot is shown in Fig. 4(d).

IV. Simulations and Results

The simulation parameter is given in table IV. Besides the HTSMA scheme, we also have simulated the single-radio protocol MMAC [3] and the hybrid multi-radio protocol HMCP [7] because all of them are distributed schemes. To compare HTSMA and MMAC fairly, the value of T_c in HTSMA is set to be the duration of data window in MMAC. For each node u in HMCP protocol, the fixed ε radios are designated for receiving and the rest switchable $\kappa(u)-\varepsilon$ radios are designated to transmit at the receiver's fixed channel ($0<\varepsilon<\kappa(u)$). In our simulations, 10 different random network topologies are generated. For each topology, the average rate is selected randomly between 0 and 1M bps for each source node. Here 40 constant bit rate (CBR) traffic flows, over UDP, are generated from 40 randomly picked nodes. The data packet generation rate for each flow is varied and simulations are performed for different number of channels and radios. The simulation results are plotted using the average values derived from 500 experiments, with a 95% confidence interval.

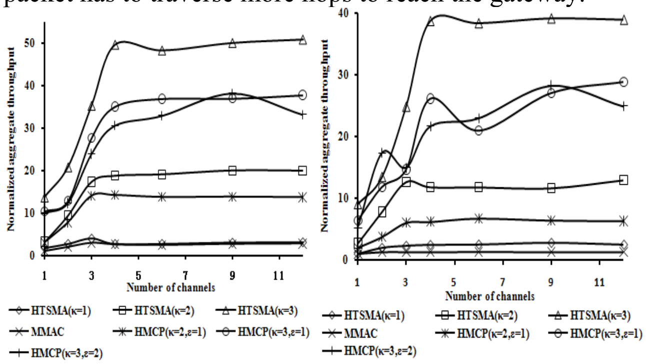
TABLE II. Simulation Parameters

Parameter	Value
Network region size	500 m×500 m, 1000 m×1000 m
Number of nodes	100
Channel capacity (C)	[1M bps, 5M bps]
Radio propagation model	Two-ray ground reflection model
Node radio transmission range	[50 m, 100 m]
Number of CBR traffic flows	40
Control message size	16 bytes
Data packet size	512 bytes
Total Memory size of node	[1M bits, 10 M bits]
Value of T_{neg}	20 ms
Value of T_c	80 ms
Adjustable parameters α, β and δ	0.3, 0.2, 0.6

(1) *Aggregate network throughput*

Fig. 5 shows the effects of varying the number of radios and the number of channels on the aggregate network throughput under two network scenarios, respectively. To observe the trend of throughput clearly, the obtained throughput is normalized to the conventional (single channel and single-radio) IEEE 802.11 for the baseline comparison. This figure shows that the capacity increases almost linearly with κ radios for up to $\kappa + 1$ channels. This suggests that in order to make the best use of available $|S_C|$ orthogonal channels, then we may need at least $|S_C|-1$ radios per node averagely. An observation is that HTSMA achieves better network throughput than MMAC because HTSMA does not need global time synchronization. Hence, it can decrease the idle time and thus increase the aggregate network throughput.

On the other hand, given multi-radio per node, the performance improvement of HTSMA over HMCP becomes more significant. The reason is that in HMCP, each node keeps the fixed radio interface for receiving even it is not receiving the packets at the current moment, which results in wastage of precious hardware resources. In HMCP, the node with the smaller number of radios may become a bottleneck, resulting in decrease of network throughput. Comparing Fig. 5(a) and (b), we also note that aggregate network throughput of all three schemes decreases with increase in the deployment area. This is due to the fact that larger deployment area indicates the data packet has to traverse more hops to reach the gateway.



(a) 500 m×500 m (b) 1000 m×1000 m

Figure 5. Normalized aggregate throughput vs. numbers of channels.

(2) *Collision ratio*

In Fig. 6, given the different number of channels, the maximal collision ratio of HTSMA in 1-radio, 2-radio, and 3-radio is 8.9%, 8.81%, and 9.47% respectively, which are larger than that of MMAC and HMCP. The reason is that the duration period for the communication between a pair of nodes in HTSMA is based on the estimated approach, instead of the exact approach as MMAC and HMCP. By this way, HTSMA may adversely increase the possibility of communication interference, but it still can enhance the channel bandwidth utilization (e.g., improving the aggregate throughput and saturation throughput) since all nodes do not need to exchange the control messages on a common channel before data communication.

As a matter of fact, in the worst case, the collision ratio of HTSMA is below 9.5%, which is still an acceptable value. While with the increase of number of channels, HTSMA has a slightly higher collision ratio because the communicating nodes (including sender nodes and receiver nodes) have to switch to more available channels to broadcast their control messages, which inevitably introduces more collisions during the channel switching. This slight increase of collision, however, is well offset by the much improved network throughput, thus becoming invisible by the end users. Besides, observing that the collision ratio of HTSMA tends to be stable with the increase of aggregate offered load, we can conclude the HTSMA scheme is applicable to the large traffic wireless networks.

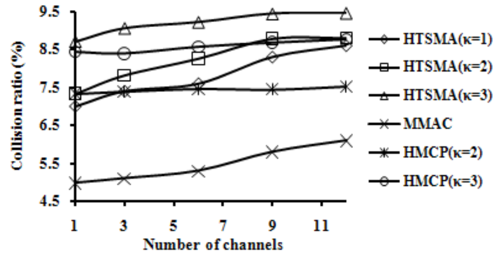


Figure 6. Collision ratio vs. number of channels in 500 m×500 m.

V. CONCLUSION

Considering the heterogeneous feature in the wireless network, a hybrid temporal-spatial multi-channel assignment scheme is proposed to solve the joint channel assignment and routing problem in WMNs. The proposed scheme does not require global time synchronization for coordinating communications or a dedicated channel for exchanging the control messages, which indicates it can be simply upgraded in the firmware without any hardware/software change. On the other hand, this scheme assigns the distinct channels to the communication nodes in a flow (toward the gateway), which is efficient for flows with a large number of hops, because channel conditions may vary in different parts of the flow. With its simplicity and flexibility, it is very suitable to be applied for large-scale WMNs. Simulation results confirm that this scheme can improve both the aggregate and saturation network throughput substantially with the acceptable collision ratio.

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