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SAM-MAC: An efficient channel assignment scheme for multi-channel ad hoc networks ☆

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Abstract

Using multi-channel MAC protocols in mobile ad hoc networks (MANETs) is a promising way to improve the throughput performance. Channel assignment, which directly determines the efficiency of the frequency utilization, is the critical part of multi-channel schemes. Current 802.11-like schemes of multi-channel MAC do not efficiently use the multiple channels due to the overhead caused by channel assignment. Moreover, the control channel saturation problem limits the number of channels of these previous schemes. In this paper, we propose a new scheme called SAM-MAC (*Self-Adjustable Multi-channel MAC*), which features with one common channel and two half-duplex transceivers for each node. A method called self-adjustment is used to reassign the channels and balance the traffic on different channels. Due to less contention in common channel and smaller channel assignment overhead, this scheme increases the throughput compared with previous approaches. Control channels are free from saturation problem and can furthermore be used for data transmission.
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Keywords: Channel assignment; Multi-channel MAC; Self-adjustment; Ad hoc networks

1. Introduction

Multi-channel MAC schemes for mobile ad hoc networks (MANETs) are attracting more and more attention nowadays, although they are still quite unexplored. Both 802.11b and 802.11a support multiple channels in infrastructure mode, but mobile nodes in ad hoc mode could only use one single channel [1]. The benefits of adopting multiple channels in MAC layer are shown in many papers. The most apparent benefit is the throughput improvement.

Nasipuri et al. [7] showed that with the same total bandwidth, dividing a single channel to multiple ones under CSMA mechanism gains a certain throughput improvement. The reason is that the

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utilization of multiple channels can mitigate collisions and contentions. In the extreme case when channel assignment is perfect and each pair of nodes have a dedicated channel, the contention and collision disappear. Therefore, in this situation, the capacity of the networks can be fully used.

The conclusion above can be only partly true because the overhead of channel assignment in a real multi-channel system cannot be ignored. The carrier sensing coupled with an efficient channel assignment mechanism is always used to select the channel with the least interference for transmission.

The other benefit we will gain from multi-channel is the fairness. We know that in 802.11 protocols, due to hidden/exposed terminal problem, in some topology scenarios, some nodes may become more disadvantaged and get less opportunity to successfully transmit than other nodes. Sometimes this situation will cause more severe problem. By moving the disadvantaged nodes to another channel, the fairness problem of 802.11 system can be alleviated. In other words, the nodes have more choices of channels than in a single channel thus better fairness can be achieved in multi-channel systems.

IEEE 802.11 DCF mode is widely used in MANETs and becomes the de facto standard. Most multi-channel research works are focused on the 802.11-like protocols. However, the previous 802.11-like multi-channel schemes cannot efficiently utilize the frequency band by reducing the channel assignment overhead. Moreover, the control channel saturation problem has significant impact on all these schemes, which results in a limited number of channels.

In this paper, we propose a new 802.11-like multi-channel MAC protocol, called *Self-Adjustable Multi-channel MAC* (SAM-MAC). The novel part of this scheme is the channel assignment, where a self-adjustment mechanism is used to balance the traffic of multiple channels, thus a more efficient utilization of channels is achieved and the throughput performance is improved. It also mitigates the control channel saturation problem greatly and consequently reduces the overhead further.

The rest of this paper is organized as follows. Section 2 reviews the related works. Sections 3 and 4 present the basic ideas and protocol description of SAM-MAC. Section 5 provides a discussion of the problems SAM-MAC has solved and the improvements it has obtained. Finally the simulation result is presented and conclusions are drawn in Sections 6 and 7, respectively.

2. Related works

There are a lot of schemes using multiple channels to realize the ad hoc MAC. Nasipuri's scheme [7] is one of the first multi-channel CSMA protocols, which uses "soft" channel reservation. If there are N channels, the protocol assumes that each host can monitor all N channels simultaneously with N transceivers. A host ready to transmit a packet searches for an idle channel and transmits on that idle channel. Among the idle channels, the one that was used for the last successful transmission is preferred. The protocol is extended by others to select the best channel based on signal power observed at the sender. This multi-channel scheme is a simple extension from the single channel MAC (802.11). It requires each node have N transceivers with one for each channel, which seems not feasible for a practical system. Despite the infeasibility, this paper gives a useful conclusion that even with the same total bandwidth, separating the channel can improve the throughput performance.

DBTMA [5] and DUCHA [13] also divide a channel into multiple sub-channels, specifically, one data channel and one control channel. Busy tones are transmitted to avoid hidden terminal problems. Through this way the spatial utilization is increased thus a better throughput performance than 802.11 can be achieved. These schemes aim at the hidden/exposed problems in multi-hop topologies.

To exploit the spectrum efficiency with multi-channel schemes, channel assignment is the focus of many other papers.

Wu et al. [11], proposed a protocol that assigns channels dynamically, in an on-demand style. This protocol, called Dynamic Channel Assignment (DCA), requires one dedicated channel for control messages and other channels are for data transmission. Each host has two transceivers, so that it can listen on both the control channel and the traffic channel simultaneously. RTS/CTS packets are exchanged on the control channel, and data packets are transmitted on the traffic channel. DCA follows an "on-demand" style to assign channels to mobile hosts, and does not require clock synchronization. This kind of schemes does not perform well when the number of channels is large because all the negotiations are fulfilled on the control channel and too much contention will cause the saturation problem over the control channel.

Similar ideas are used in [4,14]. Additionally, Zhang used two common channels to solve the hidden/exposed terminal problems in [14].

MMAC [9] uses a different way to assign the channels. This protocol does not need a separate control channel. Instead, it utilizes an ATIM-like window in the default channel to fulfil the channel negotiation. The ATIM (Ad Hoc Traffic Indication Message) window is the synchronization phase when 802.11 Power Saving Mechanism (PSM) is applied. Each node decides to be either in doze mode or awake mode according to the announcement messages heard in the synchronized ATIM window. Therefore, it has low overhead in channel assignment than DCA and need only one transceiver. However, the price of these benefits is the synchronization. It is known that the synchronization is difficult to realize in MANETs. Furthermore, how to solve the common channel saturation problem remains open.

Shi et al. [8] proposed AMCP scheme which is similar to DCA scheme except that it needs only one transceiver. This major feature comes from a direct timeout mechanism before nodes select the channels. This timeout mechanism solves the multi-channel hidden terminal problem. However, this scheme does not bring great improvement of throughput performance. The other major part of this paper is the fairness improvement. In Information Asymmetry (IA) scenario and Flow In the Middle (FIM) scenario, some disadvantaged nodes will starve due to their disadvantage in the topology to get the channel idle interval. Using multiple channels can mitigate such a starvation problem through allocating another idle channel to the disadvantaged flow timely. However, this paper only solved this problem by adjusting the disadvantaged flow to another orthogonal channel. In the case where the number of channels is much less than the number of flows, such a starvation becomes inevitable again.

A classification has been given recently in [6]. In this paper, the multi-channel schemes have been divided into four categories:

1. Dedicated Control Channel (DCC).
2. Common Hopping (CH).
3. Split Phase (SP).
4. Multiple Rendezvous using 1 radio (MR).

CH and MR use the idea of time division and frequency hopping. RICH-DP [10] is an example of CH and SSCH [2] is an example of MR. Though [6] shows MR has a better performance than DCC and SP, we exclude them (CH and MR) in our paper in that they use a very different approach in

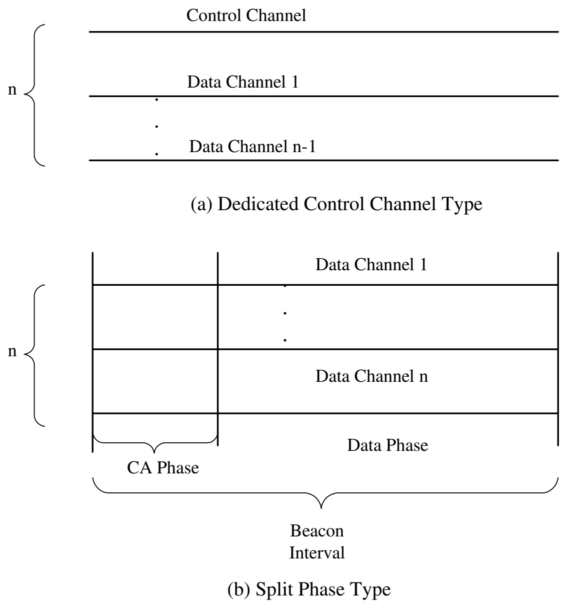

Fig. 1. Comparison of DCC type and SP type.

which time synchronization is needed and a channel hopping sequence is followed.

It is clear that the DCA scheme belongs to DCC type and MMAC belongs to SP type, according to [6]. Fig. 1 illustrates the basic difference of channel assignment (CA) between DCC type and SP type of approaches.

3. Motivations and basic idea

3.1. Motivations

The direct way to increase the throughput is to reduce the overhead caused by channel assignment. Therefore the primary goal of this design is to use the available frequency bands as efficiently as possible, thus achieve greater throughput.

If each node has a dedicated transceiver for each channel, the channel assignment will have zero overhead. This is because every channel is "visible" to every node all the time. However, due to cost consideration, the transceivers are usually fewer than the available channels. Therefore, channel assignment needs to assign the available channel resource to limited transceivers when there are data transmission requests. It is important to know the channel usage information before actual channel assignment. Otherwise, collisions may happen or the extra waiting time will be inevitable. DCC type schemes collect the channel usage information on common control channel and assign channels according to it. SP type schemes use time division to clear the past channel usage and use special phase (beginning of each time interval) to do the channel assignment on the default channel.

Both are feasible approaches to achieving throughput improvement. But using split phases needs time synchronization, which is difficult to realize in ad hoc networks. Also with split phases, how to divide time into different phases is still a two-fold problem. The first difficulty is that data packets have variable size which probably do not utilize the data phase efficiently. The second is how long the channel assignment phase should be. This is because traffic may be different and request load of channel assignment is also hard to predict. Without synchronization and time division problem, though a dedicated frequency band still means relatively high overhead, the DCC approach seems more appealing. (Here we assume the synchronization is not mandatory in the system.)

Since the transceivers are fewer than channels, the transceivers need to switch among the available channels. Therefore, two important issues cannot be ignored in the scheme design. One is the channel switching delay problem and the other is the acquirement of the channel usage information. For the first problem, a per-packet-based channel assignment scheme is not preferred. Channel assignment should be valid for a longer period. For the second problem, when a single transceiver is used, the channel assignment is difficult after data transmission because the usage information of other channels will be "invisible" during the data transmission period. AMCP, which uses only one transceiver, bypasses this difficulty in time domain [8]. It requests the nodes to wait for one data transmission period before channel assignment if the preferred channel is not available, which is also an extra overhead of channel assignment. To address these two problems, using two transceivers is a better choice. This furthermore helps to reduce the overhead by allowing data transmission on the common channel.

3.2. Basic idea

The basic idea of the proposed scheme can be summarized as follows.

- Channel 0 is used as the common channel for channel assignment and other usage. Other channels are used for data traffic, called traffic channels.
- Two half-duplex transceivers (Tx) are required for each node. Tx 0 stays on common channel and Tx 1 switches among all traffic channels dynamically.
- Every node maintains a table recording its neighbors' traffic channel number and it updates this table according to the information heard from the common channel.
- Nodes keep listening on the same traffic channel unless the channel is too busy. Channel assignment is not needed before every transmission. If nodes know the receivers' traffic channel numbers, they send RTS on the traffic channel. Otherwise, they first send query requests on common channel before RTS/CTS. When nodes need to change their traffic channels, requesting frames are also required to be sent on the common channel. The transmission on the traffic channels always follow the back-off procedure with the NAV information indicated on the common channel.
- Nodes can get the information of channel usage status by listening on the common channel. Based on this information, nodes can choose another traffic channel when current channel is too busy. This channel reassignment method is called self-adjustment and it is critical to the performance of the whole system.
- The common channel can also be used for data transmission when its traffic is relatively low.

The basic idea is based on such an observation that in all previous schemes, handshakes occur only at the common rendezvous. This mechanism makes the common rendezvous susceptible to be the whole system's bottleneck. SAM-MAC distributes the handshakes to available channels and furthermore makes the data transmission on the common channel possible. In this way, our scheme achieves higher bandwidth efficiency and removes the bottleneck from the system. According to the above, we can consider our scheme as an extension of DCC approach.

4. Protocol description of SAM-MAC

The protocol is described as follows. We first introduce the basic messages and then describe detailed procedures.

4.1. Basic messages

- *RTS/CTS*: Request to send/clear to send.
- *DATA*: Data.
- *ACK*: Acknowledgement to the data frame.
- *NCTS*: Negative clear to send.When the destination is not available, it can send a NCTS on Channel 0 to the sender to notify the NAV (Network Allocation Vector) [11]. It is used to solve the receiver blocking problem.
- *RTF/ATF*: Request to find/acknowledgement to find.If the destination node's listening traffic channel number is unknown, the sender sends RTF on Channel 0 to find it out and the destination node answers it also on Channel 0.
- *RCT/ACT*: Request to change traffic channel/acknowledgement to change traffic channel. If a sender feels the traffic channel situation unsatisfying, it will send RCT to the destination to change the sender's traffic channel to another one, on Channel 0. Then the destination node will answer back ACT when it decides which traffic channel to choose, also on Channel 0. The old traffic channel information should be included in these messages to let other nodes know the busy status of this traffic channel.
- *NBC*: NAV broadcast.Every time a receiver wants to send the RTS/CTS in traffic channel, it will copy its NAV information and Channel Number to NBC's field and send NBC on Channel 0. This message is used to avoid the hidden terminal problem caused by multi-channel. This mechanism makes the NAV be a vector instead of a scalar.

4.2. Basic operational procedures

We first describe the initial channel selection of each node. After that, how a node transmit to a node which the sender has no knowledge of the receiver's operating channel is described. When this knowledge is acquired, the transmission procedure can be simplified to the basic IEEE 802.11 procedure. Under multi-channel scenarios, dynamically adjusting the operating channel is needed for efficiently utilize the channel resource. Finally, different from other DCC schemes, our scheme can allow common channel to be used for data transmission.

4.2.1. Choosing traffic channel [initial channel selection]

With two half-duplex transceivers, one node listens on both the common channel (Channel 0) and one of the traffic channels. At the very beginning, when nodes join the networks, each of them picks randomly one traffic channel as its listening traffic channel.

Nodes keep listening on the same traffic channel until they need to transmit to some nodes on other channels or this channel is greatly saturated. The change of one node's listening traffic channel should be published to all other neighbors via the common channel.

How the sending nodes find the receiving nodes and how they change channels are described in following procedures.

4.2.2. Transmitting to a node listening on an unknown traffic channel

If the channel information of the destination node is not known, as Fig. 2 shows, the transmitting node sends a RTF on the common channel first. Since each node listens on the common channel, the destination node answers an ATF on the common channel, which includes the traffic channel information. Hereafter, the transmitting node switches its Tx 1 to the given traffic channel and starts the RTS/CTS/DATA/ACK procedure. This procedure is required when the sending nodes have no memory of the receiving nodes, e.g., when new nodes join the networks. After one transmission, the listening traffic channel number of the node is known to all its neighbors and the following transmission becomes a simpler case.

4.2.3. Transmitting to a node listening on a known traffic channel

Each node maintains a table (neighbors' channel table) recording the traffic channel number of its neighbors. Every time an ATF/ACT/NBC is transmitted on the common channel, each node listening on it updates its table. When there are data to transmit, each node looks up this table first to find out

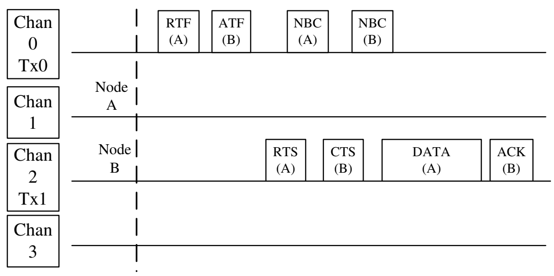

Fig. 2. Illustration of SAM-MAC procedures: unaware case.

the channel number of its destination node. Then it switches to the given traffic channel and sends data using RTS/CTS/DATA/ACK procedure, as shown in Fig. 3. If the sender node is listening on a different channel before RTS, it should send a NBC message to notify all its neighbors of the channel change after RTS is sent. The purpose is to broadcast the NAV to all its neighbors and to avoid the missing receiver problem [8] caused by the unnotified channel change. The receivers are also required to broadcast NAV via NBC frames.

The neighbors' channel table also includes the available channel lists of its neighbors. This information is stored for the purpose of channel adjustment.

4.2.4. Adjusting to a different traffic channel when busy/collision (self-adjustment procedure)

Nodes can adjust their channels to another one for the purpose of system's load balancing. When the transmitter wants the receiver to change to another traffic channel, it sends an RCT on the common channel. The current traffic channel number and the available channel list should also be included in it. The traffic channel adjustment is decided by the receiver. After the receiver decides which traffic channel is most suitable (by the channel reassignment algorithm), it sends back an ACT on the common channel and switches Tx 1 to the chosen traffic channel. Then a RTS/CTS/DATA/ACK procedure follows on the traffic channel. If the receiver cannot find a more suitable traffic channel, it sends an ACT requesting the sender to stay in the same traffic channel. The procedure described above is illustrated in Fig. 4.

If the users keep on changing channels, the system throughput as well as the QoS of the users will be degraded due to the communication overhead and switching delay. Therefore, a better channel reassignment algorithm is required to reduce the frequency of channel changing. We assume the traffic of the users is not extremely unbalanced and bursty

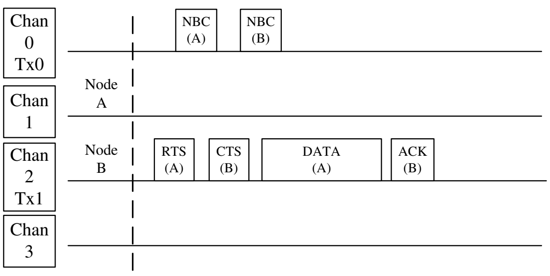

Fig. 3. Illustration of SAM-MAC procedures: aware case.

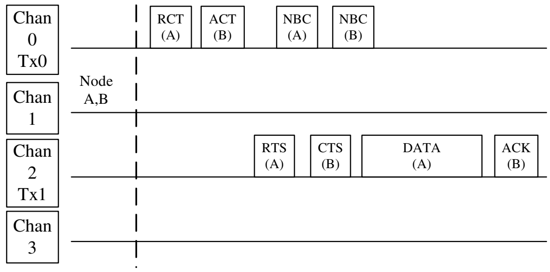

Fig. 4. Illustration of SAM-MAC procedures: self-adjustment case.

thus the traffic load can be well balanced among the channels. We can easily observe that only when a channel contains a greatly varying traffic can the frequency of channel reassignment be big. The assumption above is reasonable because the aggregate traffic in a channel is relatively constant and the fluctuation of small number of nodes' traffic will not cause great traffic load imbalance among different channels.

We use two metrics for the channel reassignment algorithm: the number of neighbors and the channel busyness ratio [12], which can both be counted or calculated from the information heard on the common channel.

4.2.5. Transmitting data on the common channel

Unlike previous DCC schemes, in which the handshakes always happen on the common channel, SAM-MAC's handshakes happen on traffic channels. This means that the common channel has much less traffic than traffic channels and data transmissions on traffic channels are less sensitive to the traffic load on common channel than previous DCC schemes. The traffic on common channel consists of RTF/ATF, RCT/ACT and NBC messages. RTF/ATF messages are needed only when a new node joins the network. NBC is needed for the nodes on a different channel to acquire the busy status of the operating channel. RCT/ACT are used for channel reassignment. Consequently, RCT/ACT and NBC form the major traffic on the common channel. As we mentioned above, when the traffic of the system is assumed not to be extremely unbalanced, the traffic on the common channel only utilize a small amount of channel resource. When the traffic on each channel is constant, this type of traffic can be ignored. Therefore, data packets can also be transmitted on the common channel.

Channel assignment algorithm allows the common channel to be chosen for data transmission when the common channel is light-loaded and the channel adjustment is needed.

After this adjustment is done through RCT/ACT, both the sender and the receiver use Tx 0 for the data transmission. Tx 1 can be turned off until adjustment to a traffic channel is required again.

4.3. Other Issues

In multi-hop topologies, the exposed terminal may be blocked by other transmissions and the sender cannot get the response from it. In SAM-MAC, the exposed terminal can send back NCTS on the common channel instead of being silent as it does in 802.11 protocol. Through this way, the exposed terminals are not vulnerable to be blocked.

Since the channel reassignment is decided by the receivers, the asymmetric information of channels between the senders and the receivers may cause unreasonable channel reassignment. For an example, a receiver may choose a channel that the sender cannot transmit at all. This is a usual case in multi-hop topologies. To avoid this inconsistency, the channel busyness ratio of the sending nodes' channels should also be considered during the channel reassignment. In the adjustment procedures, the senders should always include a channel list with a decreasing order of channel busyness ratio. The receivers store this information to the neighbors' channel table. Before the decision of channel reassignment, the receivers choose a channel with the lowest channel busyness ratio from its own traffic channel status table which is also in the available channel list of the neighbors' channel table. Therefore, the receivers would not choose a channel that cannot be accepted by the senders.

All the channels are assumed here to have the same wireless status and the channel busyness ratio can embody the real channel status of each channel. Without the consideration of frequency-selective interference, all the channel usage can be acknowledged by the NAV broadcasting, which is the virtual carrier sensing. If the physical wireless channel status needs to be considered, the second transceiver should scan around all the traffic channels to do the physical carrier sensing. In this case this overhead also needs to be considered.

5. Performance analysis

Next we evaluate the performance of SAM-MAC. Before we present the numerical simulation result, we first discuss some well-known problems and the impacts to our solution.

5.1. Multi-channel hidden terminal problem

Multi-channel hidden terminal problem is an inborn problem in the multi-channel schemes. The illustration below assumes the MAC is using RTS/CTS-like mechanism, typical in IEEE 802.11 standards. Another assumption is that each node has less transceivers than channels.

In Fig. 5, node A is communicating to node B in a common channel. Node C switches to this channel around time T1 when, unfortunately, it misses the CTS sent out by B. If node C, a hidden terminal to A, proceeds to transmit to some other node after sensing an idle channel, the signals could collide with signals sent by A at the receiver of B. We can see the reason of this problem is that node C misses the channel status, the NAV in CTS. If each node can have the same number of transceivers as channels, this problem is avoided.

For DCA [11] and MMAC [9], since handshakes occur only at the common rendezvous and each node can obtain the channel usage information by monitoring handshakes, multi-channel hidden terminal problem does not occur. For AMCP [8], with one dedicated channel and only one transceiver, multi-channel hidden terminal problem could not be easily avoided. With a direct timeout mechanism in AMCP, each node avoids this problem by acquiring the channel usage information during this period. Though this timeout mechanism helps to solve the multi-channel hidden terminal problem, it introduces an extra requirement of packet size due to the setting of the timer length.

For SAM-MAC, since handshakes are distributed, nodes on different channels are blind about each other's channel usage information if the control channel is absent. However, with one dedicated transceiver on the control channel, SAM-MAC has

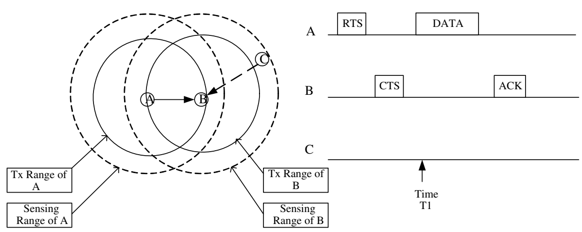

Fig. 5. Multi-channel hidden terminal problem.

the capability of knowing all channels' usage information. The message NBC is used for this purpose. With this message, every node knows the NAV of all the channels and avoid the multi-channel hidden terminal problem.

5.2. Control channel saturation problem

Though the dedicated control channel is the main overhead of DCC schemes when the channels are fewer, when the number of channels becomes greater, this overhead becomes relatively small and in some scenarios the control channel's capacity becomes the bottleneck of total throughput. In [11], this saturation problem of DCA scheme has been shown by the simulation results. Neither can MMAC overcome this problem due to the limit of ATIM window length. In [8], AMCP uses the same serial contention procedure on the control channel, so it cannot avoid such a problem, either.

For SAM-MAC, we observe that most of the handshakes before each transmission occur on different traffic channels. The major traffic on control channel, NBC messages, is not related to the handshake. Consequently the saturation problem can be overcome. Only when there are a lot of channel adjustments will the handshake traffic of control channel become heavier. This can be caused by extreme fluctuation of traffic aggregation on each channel, which is very rare.

5.3. Missing receiver problem

The nature of missing receiver problem can be explained as follows. When a transmitter wants to send a packet to a receiver which happens to tune its transceiver on another channel, the missing receiver problem occurs.

In DCA and MMAC, the dedicated control channel and the ATIM window, which are so-called common rendezvous, contains all the channel usage information. Hence this problem has no impact on them. For AMCP, after saving one dedicated transceiver on control channel, this problem becomes an issue. Since AMCP uses direct timeout mechanism when it loses channel usage information, during this delay period, the missing receiver problem is hard to overcome.

For SAM-MAC, all the channel usage information can be obtained from control channel with a dedicated transceiver. Therefore, this problem is solved in SAM-MAC.

5.4. Overhead comparison and throughput improvement

Due to the same RTS/CTS/DATA/ACK procedure in both our scheme and previous schemes, the throughput performance of the standard 802.11 protocols can be used as a reference of the performance comparison. Considering the overhead caused by channel assignment, the multi-channel schemes' maximum throughput can be expressed as follows:

$$S_{\text{mc}} = n \cdot S_{\text{standard}} - S_{\text{overhead}},$$

where n is the number of channels, as shown in Fig. 1. The above equation shows that the maximum throughput with multiple channels and multi-channel schemes is the product of the number of channel times the maximum throughput of 802.11 protocols, minus the channel assignment overhead. Obviously, the channel assignment overhead is the major indicator of the performance of a multi-channel scheme.

Referring to Fig. 1, the ratio between channel assignment phase and total beacon interval in SP type schemes is denoted as α. Therefore, the channel assignment overhead of SP type is α and the one for DCC type can be easily taken as $\frac{1}{n}$. Once the system starts up, this part of overhead caused by channel assignment is fixed no matter this part of separate resource is redundant or deficient for the channel assignment.

Under the assumption of fully utilization of the control channel (DCC type) or CA phase (SP type), we compare the overhead of two types with different numbers of channels. We use the parameters set in [9] as an example. $\alpha = 20/100 = 0.2$. When the number of channels is less than 5, the SP type of schemes have less channel assignment overhead. If this α can be smaller than 0.2, this advantage of SP type can hold in the scenarios with more channels.

However, DCC type and SP type do not have the identical channel assignment capability. Although the whole control channel can be used for channel assignment, only $1/n$ of CA phase is useful in SP type because of the requirement of a common rendezvous. To achieve the same capability of channel assignment as DCC type, SP type should require $\frac{\alpha}{n} = \frac{1}{n}$, which is impossible because there is no room left for data transmission at all. We know from previous research, [8,11], that there will be a saturation problem in control channel when 6–8 channels are fully utilized in DCC systems. According to the previous reasoning, we conclude that SP systems cannot support so much channel assignment load. Therefore, the SP systems are obviously more vulnerable to the saturation problem than DCC systems.

The comparison above shows that in single-hop topology it is impossible for multi-channel schemes to get n times throughput as in a single 802.11 channel because of the existence of channel assignment overhead. When the channel assignment load is heavier, even $n-1$ times throughput is impossible.

This limit is not the same in multi-hop topology. The multi-channel schemes allow transmission to be happened concurrently on different channels which may not be allowed in a single channel scheme. In other words, to some extent multi-channel schemes increase the spatial reuse. Even with these overheads aforementioned, the throughput improvement is more apparent when traffic is heavy or exposed/hidden terminal problems are greatly alleviated by multiple channels.

Following the overhead analysis of previous schemes, we can analyze SAM-MAC's overhead. When there are no new neighbors joining the networks, no RTF/ATF procedures are needed for a transmission. The multiple channels' traffic is assumed to be well balanced by the self-adjustment channel reassignment thus few channel adjustments (RCT/ACT) are needed. Therefore, before each data transmission only RTS/CTS are required for the handshake. Without channel assignment for each transmission, each traffic channel can obviously get a approximate throughput as a single 802.11 channel.

Furthermore, the difference from other DCC Schemes is the distribution of handshakes to traffic channels. We can model the contention as a M/M/1 queue. Assume each contender generates a packet with exponential inter-arrival rate λ and each resolution of contentions also follows the exponential distribution with the rate μ. The number of contenders in the system is m. When using previous schemes' handshake, the probability of k contenders p_k in the system and the average queue length $\overline{N}$ are

$$p_k = \left(1-\frac{m\lambda}{\mu}\right)\left(\frac{m\lambda}{\mu}\right)^k, \quad (1)$$

$$\overline{N} = \frac{1}{\left(1-\frac{m\lambda}{\mu}\right)} - 1. \quad (2)$$

After using SAM-MAC, with m contenders dispersed to n channels, the result is changed to

$$p_k = \left(1-\frac{m\lambda}{n\mu}\right)\left(\frac{m\lambda}{n\mu}\right)^k, \quad (3)$$

$$\overline{N} = \frac{1}{\left(1-\frac{m\lambda}{n\mu}\right)} - 1. \quad (4)$$

It is shown from the result that p_0 increases and $\overline{N}$ decreases. With the average contention queue length decreasing, the total duration of the handshakes decreases. This change helps to increase the throughput because the mitigated contention is the inherent overhead of CSMA/CA protocols. From the overhead point of view, this solution mitigate the handshake overhead in 802.11 protocols. According to the result of [3], the saturated throughput is independent of m when m is large enough. This is because in saturated situation the difference of number m could not bring much difference of collision probability. When m is small or the system is non-saturated, m affects $\overline{N}$ greatly and $\overline{N}$ affects greatly the throughput performance as well as the delay performance.

For all the previous schemes in which handshakes occur only at the common rendezvous, the dedicated part (the common channel or the ATIM window) cannot be used for data transmission even if it is far from saturation because of the dependency of data transmission to handshakes. However, with distributed handshakes, our scheme allows the common channel to transmit data, which makes the common channel no longer "dedicated" and achieves greater throughput than any other schemes. Therefore, S_{overhead} is further reduced and the throughput performance is improved. Additionally, since our scheme greatly alleviates the saturation problem of control channel, this scheme can support much more channels than other schemes.

6. Simulation results

NS-2 is used as the simulation platform. The simulation keeps other layer intact and only modifies the MAC layer. This simulation only cares about the throughput in MAC layer since this scheme focuses on the behavior of MAC layer. Therefore, the end-to-end throughput will not be concerned in the simulation. The throughput here means the number of all the packets successfully transmitted by MAC layer.

Shi's work [8] is used as the reference of simulation result for single-hop topology. The reason is that this paper is the latest one about the multi-channel schemes. It has given a comprehensive generalization of previous work and performance comparison. However, in multi-hop scenarios, this work focuses mainly on the fairness issue without addressing the throughput performance. Therefore, we evaluate our scheme in multi-hop scenarios through other method.

In the simulation, different nodes in the network start to deliver packets from different starting time. Channel reassignment algorithm will distribute the traffic evenly to the available traffic channels.

After this period, the channel switching is not so frequent because the nodes keep staying on the same channel unless the traffic change or connectivity cannot be satisfied. Thus, the switching delay plays a less important role in our scheme, which is ignored here.

In the following simulations, single-hop throughput performance is compared with AMCP [8] under the scenarios with different number of channels. Specifically the detailed throughput performance of 3 + 1 (3 traffic channels and 1 common channel) is shown. Multi-hop throughput performance is provided and evaluated after that.

Although the maximum aggregate throughput in single-hop scenarios can be formulated [3], it is necessary to address that the aggregate throughput in multi-hop scenarios depends much upon the topology and the coverage area. Simply saying, a bigger topology potentially has bigger aggregate throughput than a smaller one because of more nodes and more spatial reuse. For this reason, the value of aggregate throughput in multi-hop scenarios is meaningless without comparison. The benefit of our scheme in multi-hop scenarios is shown through comparing the throughput gain with different number of channels on a certain random multi-hop area.

6.1. Single-hop topology

The simulation parameters are set as Table 1.

In single-hop topologies, each node can listen to all the other nodes. As mentioned before, throughput of multi-channel schemes cannot exceed $n-1$ times of the saturated throughput of a 802.11 single channel, which intuitively is the "upper bound" throughput of DCC type schemes. However, SAM-MAC can break this "upper bound" when common channel ("CC" in the figures) is used for data transmission.

Fig. 6 shows the throughput comparison of 802.11, AMCP, and SAM-MAC with and without CC used for data transmission. Under saturated situation, SAM-MAC without CC used for data transmission can get a slightly better performance than AMCP, with the gain very close to 3. However, with CC used for data transmission, this gain can be up to 3.7.

Next simulation shows the potential multiple channels' throughput using our scheme. To get the potential multiple channels throughput, more traffic resources are needed. In this simulation, 100 nodes are used. A reference line is used for the gain comparison. We note that the common channel is not used for data transmission in this simulation in order to make the benefit of being free from saturation problem clearer.

Table 1
Simulation parameters for single-hop topology

SIFS	10 μs
DIFS	50 μs
EIFS	364 μs
Time slot	20 μs
PHY header	192 bits
MAC header	224 bits
RTS	160 bits + PHY header
CTS, ACK	112 bits + PHY header
DATA	8000 bits + PHY header + MAC header
RTF, ATF, RCT, ACT	160 bits + PHY header
Basic rate	2 Mbps
Data rate	2 Mbps
Switching delay	0
Topology range	100 m*100 m
Flow number	15
Duration	25 s

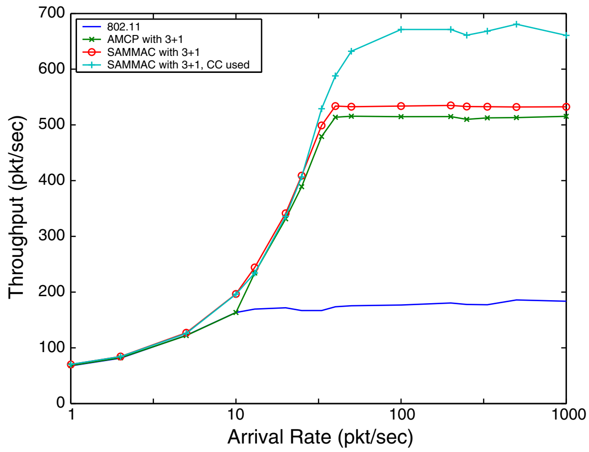

Fig. 6. Throughput gain in single-hop topology with 3 + 1 channel, with and without common channel transmitting data.

From Fig. 7 we can see the following result. The "1 channel" point stands for the standard 802.11 protocols' throughput. With the number of traffic channels being increased up to 11, the throughput of SAM-MAC is approximately linearly increasing, which shows this scheme is free from the control channel saturation problem. When 11 + 1 channels are used the throughput can achieve 9.5 times as a single 802.11 channel. The potential throughput can reach 1750 pkt/sec or even more. In this scenario, the overhead of a dedicated control channel can be almost ignored.

6.2. Multi-hop Topology

In multi-hop topology simulation, the topology range has been changed to 500 m × 500 m, the number of flows to 32, and basic rate to 1 Mbps. To get a clear comparison with the throughput in single-hop topology, CC is not used for data transmission in this simulation.

From Fig. 8, it is shown that in the topologies where the hidden/exposed terminal problems affect the throughput greatly, using multiple channels can achieve higher gains than single-hop topology case. The saturated throughput of one single channel is only 150 pkt/sec, which is much lower than the 185 pkt/sec in single-hop topology case. After using multiple channels with SAM-MAC protocol, the gain is more than in single-hop topologies. In 3 + 1 channels and 6 + 1 channels cases, the gains are more than 3 or 6 times of a single 802.11 channel's throughput, respectively. The reason that 10 + 1 cannot achieve more than 10 times gain is because the traffic cannot fully saturate the channels.

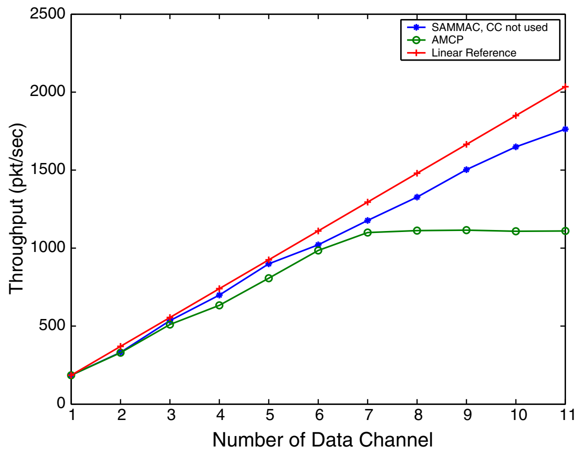

Fig. 7. Throughput gain in single-hop topology with multiple channels.

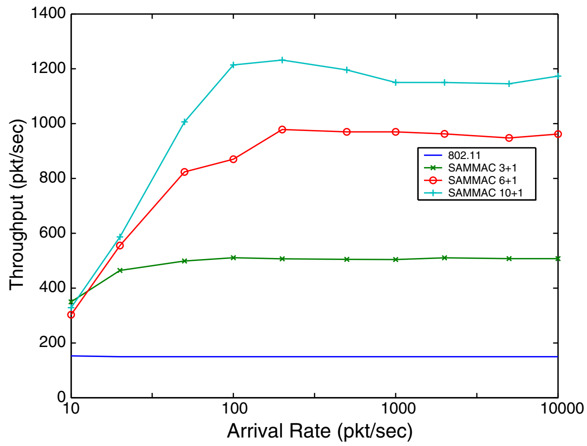

Fig. 8. Throughput gain in multi-hop topology with multiple channels.

The result of our throughput performance simulation supports the overhead analysis aforementioned.

7. Conclusions

Using multi-channel scheme helps to improve the performance of ad hoc networks, including throughput and fairness. Finding a way to use the multiple channels more efficiently helps to gain more performance improvement.

SAM-MAC can help to achieve this goal when a single channel is not enough. When the number of channels is relatively large, this scheme is more attractive because the overhead of the control channel is relatively small and the control channel saturation problem has less impact. When the number of channels is limited and the dedicated control channel becomes the major overhead, the bandwidth of the dedicated control channel can be shared by data transmission.

This scheme has obtained a better throughput performance with one more transceiver than AMCP and MMAC. It is less restricted and easily designed because of this extra transceiver. Future work includes the detailed fairness analysis and fair algorithm in channel assignment. This part can be done as one single module of channel assignment. Therefore the software is easy to be upgraded.

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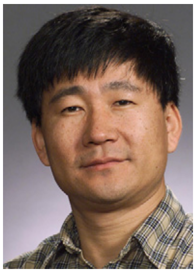

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