MAKING SAHN-MAC INDEPENDENT OF SINGLE FREQUENCY CHANNEL AND OMNIDIRECTIONAL ANTENNAS

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ABSTRACT

Provision for quality of service (QoS) for real-time traffic in multi-hop ad-hoc wireless networks with shared medium and a contention based media access control (MAC) protocol is very challenging. In our previous work we have explained the challenges in detail and provided a solution within the context of suburban ad-hoc networks (SAHN). A SAHN is a multi-hop ad-hoc network that aims to provide suburban area connectivity at broadband speed with a low initial cost and zero service charges. The solution is based on an analytical model that uses the channel access mechanism of IEEE 802.11e. The admission control mechanism of SAHN-MAC prevents any new data stream from initiating if the new stream saturates or is about to saturate any part of the network. The bandwidth reservation scheme is necessary for the admission control scheme to work properly. In this paper we extend our previous work to make SAHN-MAC independent of single frequency channel and omnidirectional antenna. The improvements have been evaluated via simulations.

KEY WORDS

Ad-Hoc Network, SAHN, QoS, Realtime, 802-11e, Admission Control, Multi Channel, Directional Antenna

1 Introduction

Several channel access mechanisms built upon TDMA (Time Division Multiple Access) [1][2] have been proposed to provide QoS in ad-hoc networks. However, MAC protocols based on TDMA require proper synchronization which may be very difficult to achieve in ad-hoc networks with unreliable links. They may need a central control station to allocate slots properly which is not a desired property of a SAHN[3][4]. To reduce channel contention the number of slots may increase in networks with large number of nodes. This may result in increased end-to-end delay for sessions[1] spreading over multiple hops since each intermediate node has to wait for particular slots to transmit data. Hence MAC protocols based on TDMA may not be suitable for a SAHN.

Alternatively contention based distributed MAC, e.g. IEEE 802.11e [5], can be used in a SAHN. However guaranteed QoS support becomes extremely challenging in contention based networks. Compared with the earlier variants of IEEE 802.11 (e.g. IEEE 802.11b), IEEE 802.11e reduces channel contention and allows better channel utilization. It provides differentiated access treatment for various classes of traffic so that real-time traffic, such as voice, video and interactive applications, can experience low jitter and latency. Real-time traffic may not be able to achieve required QoS if the network is loaded beyond certain limits. When a network exceeds its operating capacity we say that the network has become saturated. 802.11e does not provide any mechanism to prevent the network from getting saturated. MAC protocols based on CDMA (code division multiple access) over 802.11 (e.g. [6]) can improve network performance since multiple spreading codes increase channel capacity. However if the network becomes overloaded it may not be possible to provide guaranteed QoS to real-time traffic any more.

Sivavakeesar [7] has proposed a QoS aware MAC protocol based on IEEE 802.11 for multi-hop ad-hoc networks. 802.11 has been modified to accommodate MAC-level service differentiation for two types of traffic (i.e. real-time and best effort). The proposed MAC scheme switches between pure DCF (distributed coordination function) mode and combined [DCF + PCF (point coordination function)] mode depending on traffic types. Though it has been shown through simulation results that the proposed scheme improves network performance, it is not clear how the scheme will perform under saturation.

Xiao and Li [8] have presented two local data-control schemes and an admission-control scheme for ad hoc networks with IEEE 802.11e to prevent a network from getting saturated. The proposed distributed local data control scheme maps measured traffic-load condition into back-off parameters locally and dynamically. The proposed distributed admission control scheme enables each node to make decisions on the acceptances and rejections of flows. This latter feature may prevent a network from getting saturated, hence can guarantee QoS to existing data streams. Since performance evaluation of this scheme was done using single hop ad-hoc networks, it is not clear whether it can guarantee QoS to real-time traffic over multiple hops.

Like [8] SAHN-MAC also addresses the shortcomings of the legacy 802.11e. SAHN-MAC provides a solution by coupling an efficient and robust admission control and bandwidth[2] reservation scheme with IEEE 802.11e

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[1] A data stream going from one node to another to in one direction passing through intermediate nodes.

[2] Bandwidth refers to the data-carrying capacity of a transmission

and by coordinating with the network layer. However, the working mechanism of admission control scheme is different from [8]. Moreover the performance of SAHN-MAC has been evaluated using both single and multi hop networks. The admission control unit of SAHN-MAC prevents any new session from initiating if the new session saturates or is about to saturate any part of the network. This feature is not available in [7]. The bandwidth reservation scheme is responsible for proper functioning of the admission control unit. SAHN-MAC does not use existing bandwidth reservation schemes designed for wired or single hop wireless networks since they may not work properly in a multi-hop ad-hoc network with shared media. These schemes assume that the required bandwidth for a specific session should remain almost the same at all the associated nodes responsible for sending and receiving data. However, due to the RTS/CTS mechanism, multiple hops and the shared medium, the bandwidths consumed by these nodes differ. Additionally, existing bandwidth reservation schemes do not consider that the session may waste bandwidth in nodes neighboring its communication path. These aforementioned unique features of SAHN-MAC provide a robust and efficient MAC layer support for real-time traffic in a SAHN. It should be noted that the initial work [9][10] related to SAHN-MAC dealt with single frequency channel and omnidirectional antennas. This paper extends SAHN-MAC to be used in networks with multiple frequency channels and directional antennas.

This is how the rest of the paper has been organized. We have outlined the working mechanisms of SAHN-MAC in Section 2. We have extended our previous analytical model [9][10] to make SAHN-MAC independent of single frequency channel and omnidirectional antennas in Sections 3, 4 and 5. Then we have validated the correctness of our protocol in Section 6. Finally we have concluded our paper with future research directions.

2 Overview of SAHN-MAC

SAHN-MAC is an extension of IEEE 802.11e. Its basic channel access mechanism is the same as 802.11e. In this paper we will extend our previous work [9][10] to make SAHN-MAC independent of a single frequency channel and omnidirectional antenna. Here is an overview of the complete protocol, irrespective of frequency channels and antenna schemes, for estimating and reserving bandwidth. This scheme can be used as an admission control module in an ad-hoc network.

The node initiating a session s sends a session initialization request (SIREQ) packet with the required throughput[3] and the total duration of s.

An active participant[4] α, receiving SIREQ, estimates $\mathrm{U}^{\mathrm{s}}_{\alpha}$, i.e. bandwidth utilization[5] for s at α. α also calculates $\mathrm{U}^{\mathrm{s}}_{\rho}$, i.e. bandwidth utilization of each of its neighboring passive participants[6] ρ related to s.

SAHN-MAC requires each node in a network to maintain up-to-date information about the bandwidth utilization of itself and its one hop neighbors. Let us denote $\mathrm{U}^{\mathrm{Total}}_{\alpha}$ and $\mathrm{U}^{\mathrm{Total}}_{\rho}$ as the total bandwidth utilizations of α and ρ respectively. α can predict future $\mathrm{U}^{\mathrm{Total}}_{\alpha}$ by adding $\mathrm{U}^{\mathrm{s}}_{\alpha}$ to its current bandwidth utilization. Similarly α can estimate future U_{ρ} of each its neighboring passive participants. If the calculated future $\mathrm{U}^{\mathrm{Total}}_{\alpha}$ and $\mathrm{U}^{\mathrm{Total}}_{\rho}$ do not exceed a certain threshold[7], α can reserve the additional bandwidth temporarily for a certain period and forwards the SIREQ to the network layer for routing. Otherwise α drops SIREQ.

In SAHN-MAC, nodes operate in promiscuous mode. Any passive participant ρ receiving SIREQ for s estimates $\mathrm{U}^{\mathrm{s}}_{\rho}$ and reserves the additional bandwidth temporarily for a certain period.

If a SIREQ reaches its final destination, a reply (SIREP) packet is sent back. Any active and passive participants receiving SIREP update the timeout period of the reserved bandwidth with the total duration of s.

In the following sections we will show how $\mathrm{U}^{\mathrm{s}}_{\rho}$ and $\mathrm{U}^{\mathrm{s}}_{\rho}$ can be estimated for any frequency channel and antenna scheme. Initially we will consider networks with a single frequency channel and omnidirectional antennas. Then we will extend our protocol for networks with multiple frequency channels and directional antennas. We will also provide experimental results to verify the correctness and effectiveness of our protocol.

3 Estimating $\mathrm{U}^{\mathrm{s}}_{\alpha}$ and $\mathrm{U}^{\mathrm{s}}_{\rho}$ for single frequency channel and omnidirectional antenna

We have detailed the analytical model for estimating $\mathrm{U}^{\mathrm{s}}_{\alpha}$ and $\mathrm{U}^{\mathrm{s}}_{\rho}$ for single frequency channel and omnidirectional antenna in our previous work [9][10]. The working mechanism of SAHN-MAC for multiple frequency channels and directional antennas also depends on our initial analytical model. Now we will briefly present the analytical model for single frequency channel and omnidirectional antenna. In Section 4 we will generalize SAHN-MAC to be applicable in networks with multiple frequency channels and directional antennas.

First of all consider the base case for s. A network setup with only two nodes and a session s is considered as the base case for s. Here the network shown in Figure 1(a) is the base case for s. Assume that for the base case a

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medium expressed in bits per second (bps). Throughout this paper the bandwidth, required to achieve a certain throughput, will be calculated considering the overheads of all layers.

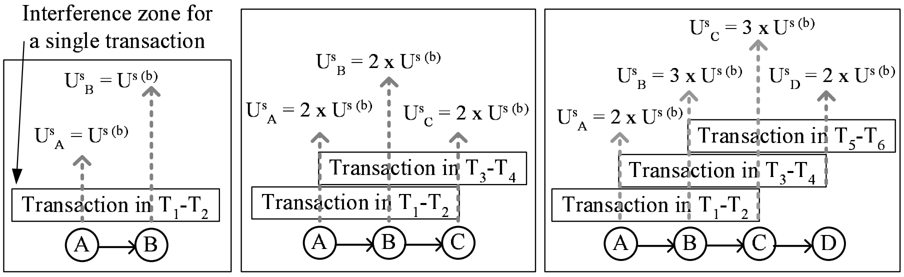
[3] Throughput is the amount of data that can be carried from one node to another in a given time period. It is usually expressed in bits per second (bps) and associated with the application layer.

[4] Nodes responsible for sending and receiving data for a particular session s will be referred to as the active participants of s.

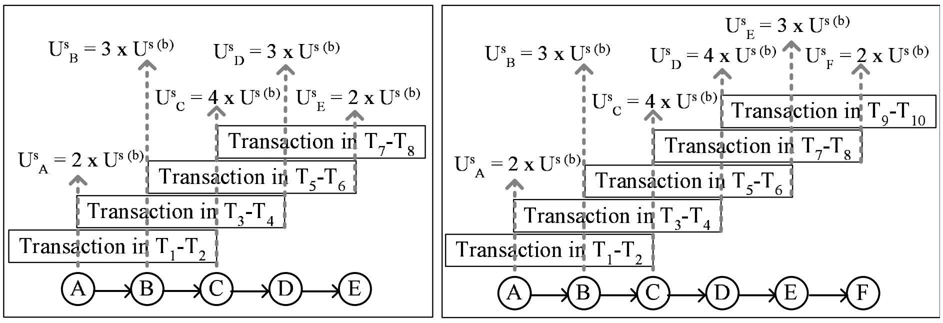
[5] Defined as $\mathrm{U} = \frac{\text{Bandwidth Consumed}}{\text{Total Bandwidth}} \times 100\%$.

[6] Passive participants refer to those neighbors of the active participants of a session s who do not actively take part in sending and receiving data for s.

[7] This threshold should be less than the saturation limit, e.g. 90%.



(a) U^s in a base case (b) U^s in a 3 node network (c) U^s in a 4 node network



(d) U^s in a 5 node network (e) U^s in a 6 node network

Figure 1. An analytical model showing $\mathrm{U^s}$ of each node in different networks. A network setup with only 2 nodes and a session s is considered as the base case for s. It is denoted by $s(b)$. Therefore $\mathrm{U^{s(b)}}$ denotes the base case bandwidth utilization for s.

single network transaction[8] takes place between $\mathrm{T_1 - T_2}$ and $\mathrm{U^s_A = U^s_B}$. If $\mathrm{U^{s(b)}}$ denotes the base case bandwidth utilization for s we can write

$$U^s_{A/B} = U^{s(b)} \tag{1}$$

Now assume that s is executed in a network with three nodes (Figure 1(b)). Within $\mathrm{T_1 - T_2}$ s will consume almost the same amount of bandwidth at all three nodes, i.e. $\mathrm{U^s_A = U^s_B = U^s_C = U^s(b)}$. Since all links are sharing the same frequency channel, A will hear the transmissions from B while another transaction occurs between B and C from time $\mathrm{T_3}$ to $\mathrm{T_4}$. Hence from $\mathrm{T_3}$ to $\mathrm{T_4}$ all three nodes will spend the same amount of bandwidth as they have spent within $\mathrm{T_1 - T_2}$. If we add all the bandwidth utilization of each node from $\mathrm{T_1}$ to $\mathrm{T_4}$ we can come up with the following expressions:

$$U^s_{A/B/C} = 2 \times U^{s(b)} \tag{2}$$

Similarly if the number of active participants of s is increased to four (Figure 1(c)) we can write:

$$U^s_{A/D} = 2 \times U^{s(b)},\ U^s_{B/C} = 3 \times U^{s(b)} \tag{3}$$

Increasing the number of active participants of s to five results in the following expression:

$$U^s_{A/E} = 2 \times U^{s(b)},\ U^s_{B/D} = 3 \times U^{s(b)},\ U^s_C = 4 \times U^{s(b)} \tag{4}$$

Equation (4) is also valid if the number of active participants of s is increased to six (Figure 1(e)) or more.

Now we will deduce a generalized form of (1)-(4). From these equations we can infer that $\mathrm{U^s_\alpha}$ of an active participant α depends on the number of transactions that α can hear transferring the same data packet for s. For example node C in Figure 1(d) can sense that the same data packet is being carried in four different transactions. Since the bandwidth utilization for each transaction is $\mathrm{U^s(b)}$, $\mathrm{U^s_C}$ of all four transactions should be $4 \times \mathrm{U^s(b)}$. This matches with (4). It should be noted that each transaction involves a specific link that connects the transmitting and the receiving active participants. For example node C in Figure 1(d) can sense that the same data packet is being carried by four links (i.e. links AB, BC, CD and DE) in four different transactions. Hence for a given session s the number of transactions can be replaced by the number of links that an active participant α can hear carrying the same data packet for s. Therefore the generalized form of (1)-(4) can be written as

$$U^s_\alpha = n \times U^{s(b)} \text{ where } n = 1,2,3... \tag{5}$$

Here n denotes the number of links that α can hear carrying the same data packet for s.

To consider the $\mathrm{U^s}$ of neighboring passive participants, let us consider the same session s used previously to be used in network shown in Figure 2. This network consists of both active (i.e. nodes A-D) and passive (i.e. nodes E-K) participants of s. The passive participants are placed in such a way that each of them could be within the

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[8] A transaction consists of the sequence RTS-CTS-SIFS-DATA-SIFS-ACK. The interference zone corresponding to a transaction spans on both sides of the communicating nodes which is represented by the rectangular boxes in Figure 1.

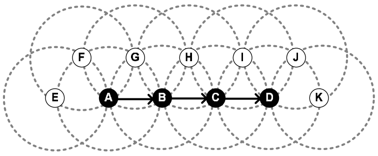


Figure 2. A communication path consisting of nodes from A to D with neighbors from E to K. Transmission range of each node has been indicated with dotted circle.

transmission range of at most 2 active participants.

Using the same arguments, used for deriving (1)-(4), the bandwidth utilization of each passive participant can be written as

$$U^s_{E/K/F/J} = U^{s(b)},\ U^s_{G/I} = 2 \times U^{s(b)},\ U^s_H = 3 \times U^{s(b)} \quad (6)$$

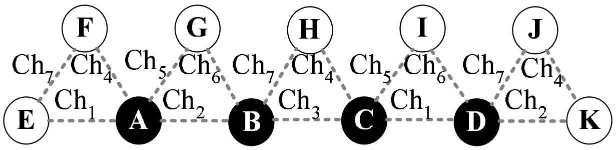
It is evident from (6) that the relationship between U^s_ρ and $\mathrm{U}^s(\mathrm{b})$ depends on the number of links that ρ can hear carrying the same data packet for s. Therefore U^s_ρ can be calculated using an equation similar to (5), i.e.

$$U^s_{\alpha/\rho} = n \times U^{s(b)} \text{ where } n = 1,2,3... \quad (7)$$

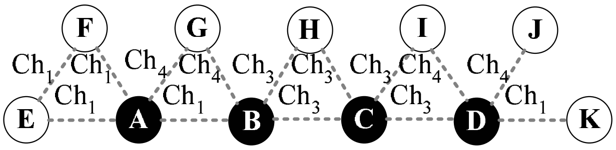
Here n denotes the number of links, joining active participants, that α or ρ can hear carrying the same data packet for s.

It should be noted that SAHN-MAC requires each active participant of a session s to estimate both U^s_α and U^s_ρ. On the other hand, passive participants need only to calculate U^s_ρ.

4 SAHN-MAC with multiple frequency channels and directional antennas



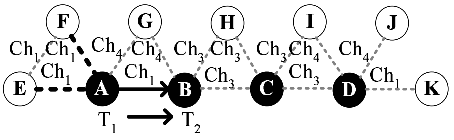
(a) This setup allows simultaneous transmissions on all links



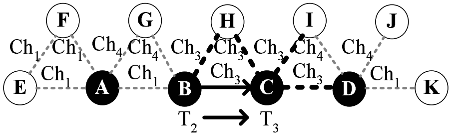
(b) This setup does not allow simultaneous transmissions on all links

Figure 3. Network setup with multiple channels.

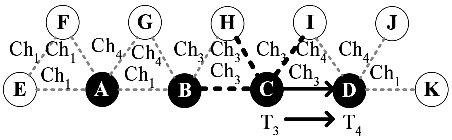
The mechanisms of SAHN-MAC described so far considered a single frequency channel to be shared by all nodes. This section extends SAHN-MAC to deal with multi-channel networks.



(a) Step 1, T_1-T_2



(b) Step 2, T_2-T_3



(c) Step 3, T_3-T_4

	Active participants	Passive participants
T_1-T_2 :	$U^s_A = U^s_B$	$= U^s_E = U^s_F = U^{s(b)}$
T_2-T_3 :	$U^s_B = U^s_C$	$= U^s_H = U^s_I = U^{s(b)}$
T_3-T_4 :	$U^s_B = U^s_C = U^s_D$	$= U^s_H = U^s_I = U^{s(b)}$
T_1-T_4 :	$U^s_A = 1 \times U^{s(b)}$, $U^s_B = 3 \times U^{s(b)}$ $U^s_C = 2 \times U^{s(b)}$, $U^s_D = 1 \times U^{s(b)}$	$U^s_E = 1 \times U^{s(b)}$, $U^s_F = 1 \times U^{s(b)}$ $U^s_G = 0 \times U^{s(b)}$, $U^s_H = 2 \times U^{s(b)}$ $U^s_I = 2 \times U^{s(b)}$, $U^s_J = 0 \times U^{s(b)}$

(d) U of each active and passive participants

Figure 4. Measuring U of active and passive participants in a network with multiple channels. Darker lines in (a)-(c) represent the links hearing the same transaction.

Consider the network in Figure 3(a). Here A establishes a session s with D. Here each node is equipped with at most 4 network cards for 4 neighbors using 4 non-overlapping frequency channels. Frequency channels are distributed among nodes in such a way that simultaneous transmissions of the same frequency channel do not interfere with each other. This enables all links to be operational concurrently. That is for example when B receives a data packet from A, it can transmit another data packet to C simultaneously. This implies that an active participant can hear the transactions of the same data packet on at most two links, but these links do not interfere each other like the network with single frequency channel discussed in the previous section. It should be noted that with such setup there is no passive participant. Hence U^s_α of each active participant should be equal to $\mathrm{U}^{s(b)}$. In other words (7) can be used where the value of n will always be 1.

In a large network it may not be possible to allocate a non-overlapping frequency channel to each link. It means that in a multi-channel network some of the links may have to share the same frequency channel. A similar network setup has been shown in Figure 3(b). Though the network involves multiple channels, we can claim that for a given session s the bandwidth utilization of any node (either active or passive participant) will depend on the number of links that the node will hear carrying the same data packet for s.

Our claim should be effective for of two reasons: (a) The smallest unit of bandwidth utilization for s of any node is $\mathrm{U}^{\mathrm{s(b)}}$ and (b) How many units will constitute the $\mathrm{U}^{\mathrm{s(b)}}$ of a node really depends on how many links (i.e. transactions) the node will sense carrying the same data packet for s.

To support our claim here is an example with a session s consisting of a single data packet and the network shown in Figure 3(b). Node A operates at frequency channels Ch_1 and Ch_4. It cannot hear any transaction happening in link BC since link BC operates at Ch_3. The only transaction it hears is the one involving link AB (Figure 4(a)). Hence $\mathrm{U}^{\mathrm{s}}_{\mathrm{A}} = 1 \times \mathrm{U}^{\mathrm{s(b)}}$, which satisfies our claim.

On the other hand, B can hear the transactions of three links since it shares frequency channels with links AB, BC and CD (shown in Figure 4(a)-(c)). Therefore, $\mathrm{U}^{\mathrm{s}}_{\mathrm{B}}$ becomes $3 \times \mathrm{U}^{\mathrm{s(b)}}$ which also matches our claim. Figure 4(d) summarizes the U of all active and passive participants involved in the transactions for session s.

With the same explanation we can justify that U^{s} of each active and passive participant of s can be achieved using (7). It should be noted this equation should be applicable to networks with directional antennas as well.

5 Determining the value of n

A node broadcasts the following information up to 2 hop neighbors: (a) its geographical location, (b) list of its neighbors and their geographical locations, (c) frequency channels allocated to each neighbor, (d) transmission directions used for each neighbor, and (e) transmission ranges assigned to each neighbor.

Each node records such information from all the neighbors residing within 2 hop radius. This information is needed for determining the value of n. A node does not need to broadcast this information very often if the network is quasi-static (i.e. nodes are not mobile) in nature like a SAHN. Active or passive participants of a session can use the 2 hop neighboring information and the same algorithm presented in [10] to find the value of n.

6 Performance of SAHN-MAC

In this section we compare the performance of SAHN-MAC and 802.11e with respect to end-to-end delay, throughput and delivery ratio for networks with directional antennas. Delivery ratio of a session can be defined as the percentage of data received successfully at the final destination of that session.

We have used GloMoSim (version 2.02) for simulating various layers and wireless media. 77 nodes were placed on a 3000 meter by 3000 meter flat terrain. Nodes were separated by 240 meters and each node had at most six neighbors. Each node was equipped with three network interface cards where each of them were connected to a directional antenna. Each antenna was assumed to have the same transmission range (i.e. 240 meters) and be capable of forming thin beam for communication. A node could connect to at most three neighbors simultaneously. We have used IEEE 802.11e in the link layer. The physical layer modulates/demodulates signals using OFDM (Orthogonal Frequency Division Multiplexing) with a transmission rate of 54 Mbps.

Each test case was executed for 120 seconds, consisted of twenty four source and destination pairs, and contained forty eight 4.6 Mbps UDP type CBR sessions. The source and destination pairs and their corresponding sessions were evenly distributed in the whole network. In each test case a new session was added every 1 second interval. For simplicity all established sessions were of the same access category and executed till the end of the simulation run. The path lengths (in terms of total number of active participants) of all sessions in each test case were kept fixed. However among various test cases they were varied from 4 to 6. The source and destination pairs were also varied among various test cases. Each test case was compared with both SAHN-MAC and 802.11e. The average values of all performance metrics were recorded at 200 millisecond interval. We have used DSR (Dynamic Source Routing [11]) as the underlying routing protocol.

The simulation results have been presented in Figure 5. Additions of new sessions increased network load. Unlike 802.11e, SAHN-MAC did not allow any new session to initiate if the session could choke existing sessions. Results show that the network performance degrades at the beginning for both SAHN-MAC and 802.11e. However, with SAHN-MAC the network became stable after a short while whereas with 802.11e the performance kept degrading till the end of the simulation. Therefore we can infer that SAHN-MAC can maintain fairly stable network performance compared to 802.11e which is very important for ensuring QoS for real-time traffic.

7 Conclusion

We have extended SAHN-MAC to be applicable in networks with multiple frequency channels and directional antennas. Simulation results based on single frequency channel and omnidirectional antennas (presented in a previous work [10]) as well as directional antennas (this paper) show that SAHN-MAC can prevent network from getting saturated, hence can ensure desired QoS to existing data streams. In future we would like to build a scheduling scheme at the MAC layer to handle different classes of traffic efficiently.

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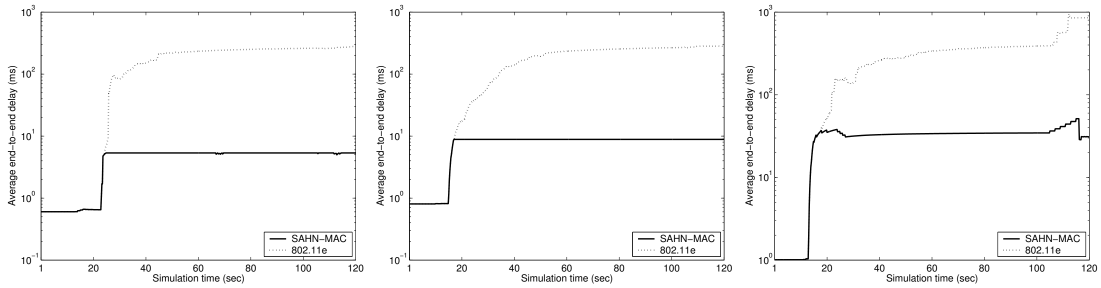
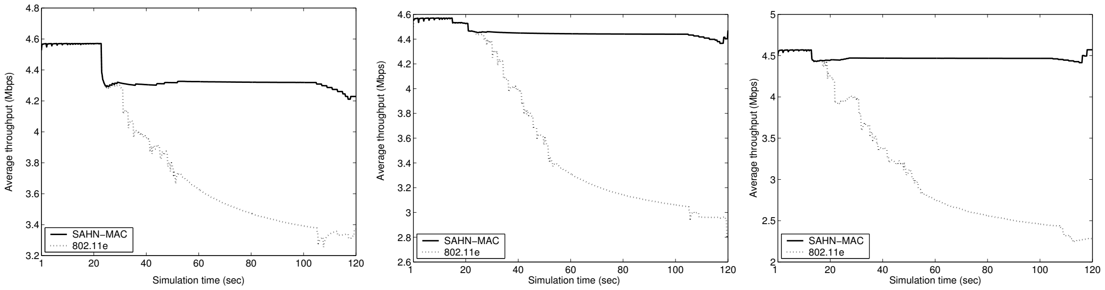
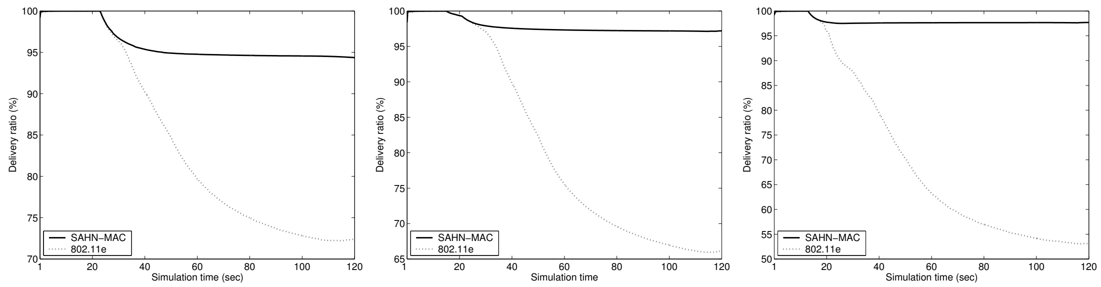


(a) Path length of each session is 4 (b) Path length of each session is 5 (c) Path length of each session is 6



(d) Path length of each session is 4 (e) Path length of each session is 5 (f) Path length of each session is 6



(g) Path length of each session is 4 (h) Path length of each session is 5 (i) Path length of each session is 6

Figure 5. Performance results using SAHN-MAC and 802.11e. (a)-(c), (d)-(f) and (g)-(i) show performance results in terms of average end-to-end delay, average throughput and delivery ratio respectively.

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