Challenges and a Solution to Support QoS for Real-Time Traffic in Multi-Hop Ad-Hoc Networks

Muhammad Mahmudul Islam, Ronald Pose, Carlo Kopp
School of Computer Science and Software Engineering, Monash University, Australia
{sislam,rdp,carlo}@csse.monash.edu.au

Abstract— **In this paper we explain why trivial solutions are inadequate for supporting deterministic QoS (quality of service) for real-time traffic in multi-hop ad-hoc networks with shared medium and contention based MAC (media access control) protocols. We also provide our initial work to address this issue with an analytical model within the context of suburban ad-hoc networks (SAHN). A SAHN is a multi-hop ad-hoc network. The analytical model is based on the channel access mechanism of a contention based MAC protocol such as the IEEE 802.11e. We refer to the improved IEEE 802.11e as SAHN-MAC. SAHN-MAC provides a distributed admission control and bandwidth reservation scheme by extending the features of IEEE 802.11e and coordinating with the network layer. The proposed admission control mechanism aims to prevent 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. These unique features make SAHN-MAC different from existing protocols. The proposed mechanisms have been verified via simulations.**

Keywords– Ad-Hoc, SAHN, MAC, QoS, Real-time, 802-11e, Admission Control, Bandwidth reservation

I. Introduction

Ad-hoc networks use wireless links for communicating with other nodes. The communication can be over multiple hops. Due to the shared nature of wireless media and multiple hops it is very challenging to provide desired QoS (end-to-end delay, throughput, delivery ratio etc) to various data streams. This requires efficient and robust protocols to be deployed at each layer. Proper coordination among these protocols is also necessary to achieve overall network performance. Moreover without the support from the MAC layer, the QoS guarantee of higher layers is not possible.

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][4][5][6]. 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 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 [7], 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. [8]) 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 anymore.

Sivavakeesar [9] 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). 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 [10] 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. 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.

SAHN-MAC also addresses the shortcomings of the legacy 802.11e. It provides a solution by coupling an efficient and robust admission control and bandwidth[1] reservation scheme with IEEE 802.11e and by coordinating with the network layer. However the working mechanism of admission control scheme is different from [10]. More-

[1]Bandwidth refers to the data-carrying capacity of a transmission medium expressed in bps.

over SAHN-MAC works for both single and multi hop adhoc 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 [9]. 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 data stream s 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 s 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.

This is how the rest of the paper has been organized. We have defined some commonly used terms and described our simulation setup tool in Section II and Section III respectively. We have explained various challenges to support QoS for real-time traffic in multi-hop ad-hoc networks in Sections IV, V and VI. Then we have provided a solution to the challenges by outlining the working mechanisms of SAHN-MAC in Section VII. We have built analytical models to find different parameters of SAHN-MAC in Sections VIII and IX. Then we have validated the correctness of our proposed scheme in Section X. Finally we have concluded our paper with future research directions.

II. Definitions

Session (s): A data stream going in one direction and passing through intermediate nodes.

Throughput: 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.

Bandwidth: Bandwidth and throughput of a specific session correspond to the same value at the application layer. However, any network transaction adds a number of headers to each data packet at each layer. Moreover, the channel access mechanism of 802.11 needs additional time slots for accommodating RTS, CTS and ACK packets with each data packet. Due to these overheads the bandwidth required at the physical layer for a given session is always greater than that of the application layer.

Throughout this paper the bandwidth, required to achieve a certain throughput, will be calculated considering the overheads of all layers.

Active participant (a): Nodes responsible for sending and receiving data for a particular session s will be referred to as the active participants of s.

Passive participant (p): 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.

Link: A directional communication channel between two neighboring nodes.

Bandwidth utilization (U): Defined as $\text{U} = \frac{\text{Bandwidth Consumed}}{\text{Total Bandwidth}} \times 100\%$.

III. Simulation setup

Throughout this paper, if not mentioned explicitly, we have considered the following setup for our analyses and simulations. We have used GloMoSim (version 2.02) for simulating various layers and wireless media. Nodes are separated by at most 240 meters, use same transmission power with an transmission range of maximum 240 meters, share the same frequency channel and use 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 and uses a single network card with a single omnidirectional antenna. Each session consists of CBR (Constant Bit Rate) traffic using UDP and routed using DSR (Dynamic Source Routing [11]).

IV. Effect of Saturation

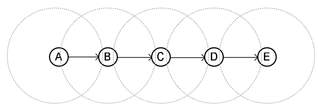

Fig. 1. A network with 5 nodes.

Consider a network setup shown in Figure 1 with 5 nodes (A, B, C, D and E). Transmission range of each node has been shown with dotted circles. Here A establishes a 2.6 Mbps session with E with the highest access category (AC) of 802.11e. Each packet is 512 bytes long.

To observe the effect of network performance under saturation, we have added an additional flow at A with destination E and increased its throughput so that the combined load exceeds the transmitting/receiving capacity of some of the active participants. It should be noted that due to the overheads of different layers, the maximum achievable throughput for the given network setup (i.e. 5 nodes) and packet size (i.e. 512 bytes) is about 5.1 Mbps [12][13]. The network began to saturate when the additional flow reached a throughput of 2.1 Mbps. If the additional flow was assigned a lower AC, the original data flow would be less affected due to the channel access mechanism of 802.11e. Hence the additional flow and original flow were of the same AC.

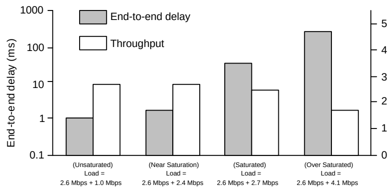

Fig. 2. Effect of saturation on end-to-end delay and throughput.

Nodes	U (%)	Nodes	U(%)
A	36.983	F	17.925
B	54.915	G	38.469
C	72.619	H	56.106
D	54.702	I	56.030
E	35.546	J	38.286
		K	17.747

TABLE I

U of all active and passive participants of a 3.4 Mbps session between A and E in Figure 3 with 512 bytes packets.

Simulation results (Figure 2) showed that the end-to-end delays of original data flow remained within 0.9-1.2 milliseconds until active participants became saturated. When some of the active participants began to saturate, the end-to-end delay degraded significantly. Throughput was also degrading but not significantly until the network was over saturated. At over saturation the end-to-end delay increased almost by 550% (559 ms) and the throughput degraded by 35% (1.7 Mbps).

If the active participants remain unsaturated, they can get their proper share of their respective links to transmit packets at intervals adequate to achieve the desired end-to-end delay and throughput. This prevents packets with higher AC from waiting in the output queue for too long. However if one or more active participants become saturated, they cannot access the channel at desired intervals. Moreover the back-off mechanism of 802.11e adds additional delays to any packet waiting for the channel to become free. Consequently the average end-to-end delay degrades considerably. The average throughput also degrades but the rate of degradation is less than that of the average end-to-end delay.

So we can claim that the desired performance of a session with higher AC can be achieved if its active participants are not saturated. SAHN-MAC achieves this by requiring any session to reserve bandwidth during its initialization phase. A session is not established if its active/passive participants tend to saturate.

V. Effect of Multiple Hops on U

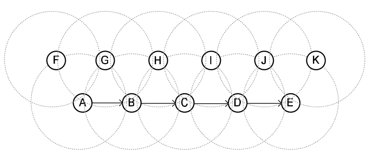

Fig. 3. A network with 11 nodes.

Now we will see what effect a multi-hop session may have on U. Consider a network setup shown in Figure 3 with 11 nodes. Transmission range of each node has been shown with dotted circles. Let us assume that A establishes a 3.4 Mbps session s with E where each packet is 512 bytes long. We have logged U of each node every 1 min and averaged them at the end of each run.

The second column of Table I represents average U of each active participants. It shows that in a shared frequency channel, i.e. shared medium, the U of all active participants cannot be considered the same. This is due to the channel access mechanism of 802.11e whereby the nodes near the center of the communication path of a session tend to sense the frequency channel to be busy more often than the nodes towards its ends. Therefore in a multi-hop ad-hoc network a bandwidth reservation protocol must not assume that the required bandwidth for a specific data session will remain almost the same at all active participants.

VI. Effect of Neighboring Sessions

A session in multi-hop ad-hoc network may waste bandwidth in its passive participants. This is because a passive participant of a session senses the channel to be busy while its neighboring active participants transmit data. Let us consider the example from the previous section. Session s wastes some bandwidth in its passive participants F-K. The fourth column of Table I shows the U of each passive participants. While s is in progress let us add another 3.4 Mbps session s' between G and K. Since s and s' have the same configuration, their U pattern in their active and passive participants should be similar. Therefore the addition s' will increase the U of some of the nodes beyond their working limits. For example, the U of C has to be almost 128.724% (72.619 + 56.105) for the normal operation of both sessions which is more than the working capacity of C. Consequently the performance of both s and s' will be degraded. The simulation results show that the end-to-end delay and the throughput of both s and s' degraded almost by 100% and 6% respectively. Therefore in a multi-hop ad-hoc network a bandwidth reservation protocol must consider the U of the passive participants to avoid overloading some parts of the network.

VII. A Solution by SAHN-MAC

SAHN-MAC is an extension of IEEE 802.11e that provides a solution for supporting deterministic QoS for real-time traffic in multi-hop ad-hoc networks. Its basic channel access mechanism is like 802.11e. The admission control scheme of SAHN-MAC prevents the active/passive participants of a session from getting saturated. The bandwidth reservation scheme ensures that the admission control scheme can work properly. This is how SAHN-MAC works:

- The node initiating a session s sends a session initialization request (SIREQ) packet with the required throughput and the total duration of s.
- An active participant a, receiving SIREQ, estimates $\mathrm{U}_{\mathrm{a}}^{\mathrm{s}}$, i.e. bandwidth utilization for s at a. a also calculates $\mathrm{U}_{\mathrm{p}}^{\mathrm{s}}$, i.e. bandwidth utilization of each of its neighboring passive participants p 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 $\mathrm{U}_{\mathrm{a}}^{\mathrm{Total}}$ and $\mathrm{U}_{\mathrm{p}}^{\mathrm{Total}}$ as the total bandwidth utilizations of a and p respectively. a can predict future $\mathrm{U}_{\mathrm{a}}^{\mathrm{Total}}$ by adding $\mathrm{U}_{\mathrm{a}}^{\mathrm{s}}$ to its current bandwidth utilization. Similarly a can estimate future U_{p} of each its neighboring passive participants. If the calculated future $\mathrm{U}_{\mathrm{a}}^{\mathrm{Total}}$ and $\mathrm{U}_{\mathrm{p}}^{\mathrm{Total}}$ do not exceed a certain threshold[2], a can reserve the additional bandwidth temporarily for a certain period and forwards the SIREQ to the network layer for routing. Otherwise a drops SIREQ.
- In SAHN-MAC nodes operate in promiscuous mode. Any passive participant p receiving SIREQ for s estimates $\mathrm{U}_{\mathrm{p}}^{\mathrm{s}}$ 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 section we will show how $\mathrm{U}_{\mathrm{a}}^{\mathrm{s}}$ can be estimated in multi-hop ad-hoc networks with a single frequency channel and omnidirectional antennas. We will also provide experimental results to verify the correctness of our protocol.

VIII. Estimating $\mathrm{U}_{\mathrm{a}}^{\mathrm{s}}$

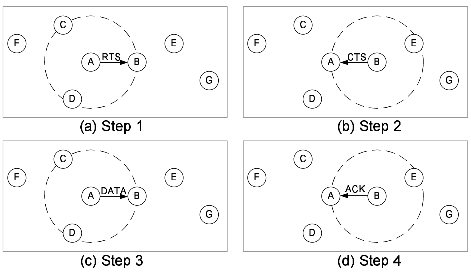

Fig. 4. The process of sending a data packet from A to B using the channel access mechanism of 802.11.

Let us consider a session s that involves sending a single data packet from A to B in Figure 4. To send the data packet successfully to B both A and B reserve the surrounding channel (denoted by dotted circle) until all the steps (i.e. Steps 1 to 4) are finished. Steps 1 to 4 form a single network transaction. The time required to accomplish a network transaction determines the bandwidth utilization for sending the data packet from A to B. Since both A and B remain busy during all four steps, $\mathrm{U}_{\mathrm{A}}^{\mathrm{s}}$ and $\mathrm{U}_{\mathrm{B}}^{\mathrm{s}}$ should be almost the same. If all the links in Figure 4 share the same frequency channel, s should consume almost the same amount of bandwidth at the neighboring nodes C, D and E. With this basic principle of calculating bandwidth utilization, we will build an analytical model for estimating $\mathrm{U}_{\mathrm{a}}^{\mathrm{s}}$ and $\mathrm{U}_{\mathrm{p}}^{\mathrm{s}}$.

We use a session s that consists of a single data packet for our analytical model. We also assume that nodes are aligned in a straight line and the transmission of any node can reach up to one neighbor in each direction.

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 5(a) is the base case for s. Assume that for the base case a single network transaction takes place between $\mathrm{T}_1 - \mathrm{T}_2$. Based on the basic principle, described at the beginning of this section, we can say $\mathrm{U}_{\mathrm{A}}^{\mathrm{s}} = \mathrm{U}_{\mathrm{B}}^{\mathrm{s}}$. If $\mathrm{U}^{\mathrm{s(b)}}$ 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 5(b)). Within $\mathrm{T}_1 - \mathrm{T}_2$ s will consume almost the same amount of bandwidth at all three nodes, i.e. $\mathrm{U}_{\mathrm{A}}^{\mathrm{s}} = \mathrm{U}_{\mathrm{B}}^{\mathrm{s}} = \mathrm{U}_{\mathrm{C}}^{\mathrm{s}} = \mathrm{U}^{\mathrm{s}}(\mathrm{b})$. 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 T_3 to T_4. Hence from T_3 to T_4 all three nodes will spend the same amount of bandwidth as they have spent within $\mathrm{T}_1 - \mathrm{T}_2$. If we add all the bandwidth utilization of each node from T_1 to T_4 we can come up with the following expressions:

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

If the number of active participants of s is increased to four (Figure 5(c)), there will be three transactions occurring between T_1 to T_6. Both A and D can hear at most two transactions whereas both B and C can hear three of them. Hence the bandwidth utilization of each active participants can be expressed as follows:

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

Increasing the number of active participants of s to five results in four transactions (Figure 5(d)) to take place between T_1 to T_8. Node in the middle, i.e. C, is able to listen to all four transactions. This number decreases as we move towards the ends. The bandwidth utilizations of each node during $\mathrm{T}_1 - \mathrm{T}_8$ become

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

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

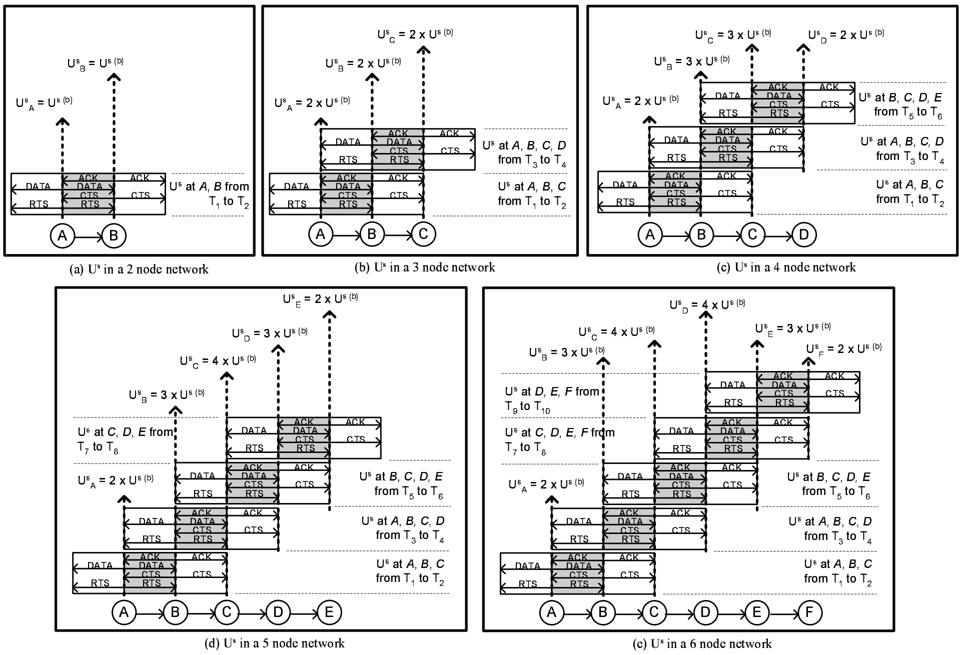

Fig. 5. An analytical model showing U^s of each node in different networks. A network setup with only 2 nodes and a session s is considered as the base case for s. It is denoted by $s(b)$. Therefore $U^{s(b)}$ denotes the base case bandwidth utilization for s.

Equation (4) is also valid if the number of active participants of s is increased to six (Figure 5(e)).

Now we will deduce a generalized form of (1)-(4). From these equations we can infer that U^s_a of an active participant a depends on the number of transactions that a can hear transferring the same data packet for s. For example node C in Figure 5(d) can sense that the same data packet is being carried in four different transactions. Since the bandwidth utilization for each transaction is $U^s(b)$, U^s_C of all four transactions should be $4 \times U^s(b)$. This matches with (4). It should be noted that each transaction involves a specific link that joins the transmitting and the receiving active participants. For example node C in Figure 5(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 a can hear carrying the same data packet for s. Therefore the generalized form of (1)-(4) can be written as

$$U_a^s = x \times U^{s(b)} \quad \text{where } x = 1,2,3... \qquad (5)$$

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

If the number of packets per second in a session is p and the duration of channel being blocked for the given packet size is $T_{ChannelBolcked}$[3] seconds, $U^{s(b)}$ can be calculated in the following way:

$$U^{s(b)} = p \times T_{ChannelBolcked} \times 100 \ \% \qquad (6)$$

Here is an example for calculating $U^{s(b)}$. Assume that we want to calculate $U^{1.6\text{Mbps}(b)}$ for a 1.6 Mbps session where each data packet is 400 bytes long. Here $T_{DATA} = 20 + 4 \times \lceil \frac{16+6+8\times(34+400)}{216} \rceil = 88$ μsec, $T_{RTS} = T_{CTS} = T_{ACK} = 24$ μsec and $T_{SIFS} = 16$ μsec. Now $T_{ChannelBolcked}$ becomes $24 + 16 + 24 + 16 + 88 + 16 + 24 = 208$ μsec. Hence $U^{1.6\text{Mbps}(b)} = \frac{1.6\times10^6}{8\times400} \times \frac{208}{10^6} \times 100 = 10.4$ %.

When an active participant receives a SIREQ for a session s, it can predict the additional bandwidth utilization for s using (5). However, this equation does not consider the U^s of neighboring passive participants. We will deal with this issue in a future paper.

IX. Determining the value of x

A node broadcasts the following information up to two hop neighbors:

(1) its geographical location
(2) list of its neighbors and their geographical locations
(3) transmission ranges assigned to each neighbor

Each node records such information from all the neighbors residing within two hop radius. This information are needed for determining the value of x. 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

[3] In 802.11 $T_{ChannelBolcked} = T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + T_{DATA} + T_{SIFS} + T_{ACK}$.

like a SAHN. Now we will show how an active participant of a session s can use the aforementioned information to find the value of x.

A. Determine x of $\mathrm{U}_\mathrm{a}^\mathrm{s}$ by an active participant a

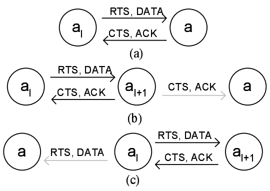

Fig. 6. Possible positions of an active participant a from where it may hear the transactions related to s.

An active participant a receiving a SIREQ for a session s calculates $\mathrm{U}^{\mathrm{s(b)}}$. Then it goes through the following steps to determine the value of x to estimate $\mathrm{U}_\mathrm{a}^\mathrm{s}$:

(1) Initializes x to 0.

(2) Makes a list of all active participants of s within two hop radius of a. The nodes in this list should be ordered based on the hopping sequence of the data packets of s. Assume the list consists of $a_1, a_2...a_n$ including a.

(3) For each $a_l \in \{a_1, a_2...a_n\}$, a increments x by 1 if any of the following cases is true:

- a_l is an immediate upstream neighbor
- $a_l = a$, e.g. Figure 6(a)
- a_l is a two hop neighbor as shown in Figure 6(b) and the transmission range corresponding to the link $a_{l+1}a_l$ match with that of $a_{l+1}a$
- a_l is an immediate downstream neighbor as shown in Figure 6(c) and the transmission range associated to the link $a_l a_{l+1}$ match with that of the link $a_l a$

X. Validating SHAN-MAC

Here we have validated the correctness of the bandwidth estimation scheme of SAHN-MAC using some simple test cases.

First of all each test dealt with a single session where all the active participants formed a straight communication path and each of them could be within the transmission range of at most 2 other active participants. Figure 1 is an example of such networks. The number of active participants and the traffic load of various sessions were varied from from 2 to 11 and 45 Kbps to 8 Mbps respectively to form various test cases. We have logged BWU of each node every 1 minute and averaged them at the end of each run. Results show that SAHN-MAC was able to estimate bandwidth utilization of each active participant correctly with almost 93% accuracy.

We have also applied SAHN-MAC in a network with 70 nodes in a 3000 meter by 3000 meter flat terrain. Each node had at most six neighbors. For each test case we have established 20 sessions with same hop count and access category but different source and destination pairs. We have verified hop counts among various test cases from 3 to 5. We have measured the utilization of each session for each active and passive participants. At present SAHN-MAC does not consider passive participants for estimating utilization of each session. As a result it was able to predict utilization of each session with on an average 85% accuracy. We hope to increase the prediction accuracy in future by considering passive participants, i.e. both $\mathrm{U}_\mathrm{a}^\mathrm{s}$ and $\mathrm{U}_\mathrm{p}^\mathrm{s}$ are calculated.

XI. Conclusion

We have discussed the challenges and presented a solution for supporting deterministic QoS for real-time traffic in multi-hop ad-hoc networks. We are extending our protocol to estimate $\mathrm{U}_\mathrm{p}^\mathrm{s}$ and measure performance. We would also like to work with multiple frequency channels and directional antennas [6] and build a scheduling scheme at the MAC layer to handle different classes of traffic efficiently. We would also like to investigate the performance of SAHN-MAC in both simulated and real environment.

References

[1] Jimmi Grönkvist. Assignment methods for spatial reuse TDMA. In *MobiHOC*, pages 119–124. IEEE Press, 2000.

[2] Marvin Sanchez G. Multiple Access Protocols with Smart Antennas in Multihop Ad Hoc Rural-Area Networks. citeseer.nj.nec.com/sanchez02multiple.html.

[3] R. Pose, C. Kopp. Bypassing the Home Computing Bottleneck: The Suburban Area Network. *3rd Australasian Computer Architecture Conference*, pages 87–100, Feb 1998.

[4] M. M. Islam, R. Pose, C. Kopp. A Hybrid QoS Routing Strategy for Suburban Ad-Hoc Networks. *ICON 2003*, pages 225–230, Sep 28 - Oct 1 2003. Sydney, Australia.

[5] M. M. Islam, R. Pose, C. Kopp. A Router Architecture to Achieve Link Rate Throughput in Suburban Ad-Hoc Networks. *A Omondi and S Sedukhin (eds), LNCS, Springer-Verlag, Berlin, Germany*, pages 395–407, 2003.

[6] M. M. Islam, R. Pose, C. Kopp. Multiple directional antennas in suburban ad-hoc networks. In *ITCC*, volume 2, pages 385–399, Apr 2004.

[7] IEEE Std802.11e/D3.3.2. IEEE 802.11 WG, Draft Supplement to Part 11:Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Medium Access Control (MAC) Enhancements for Quality of Service (QoS), Nov 2002.

[8] Alaa Muqattash and Marwan Krunz. Cdma-based mac protocol for wireless ad hoc networks. In *MobiHOC*, pages 153–164. ACM Press, 2003.

[9] S. Sivavakeesar. Quality of Service Aware MAC Based on IEEE 802.11 for Multihop Ad-Hoc Networks. In *WCNC*, pages 1482–1487, March 2004.

[10] Yang Xiao and Haizhon Li. Local Data Control and Admission Control for QoS Support in Wireless Ad Hoc Networks. *IEEE Transaction on VT*, 53(5):1558–1572, Sep 2004.

[11] D.B. Johnson and D.A. Maltz. *Dynamic Source Routing in Ad-hoc Wireless Networks*, chapter 5, pages 153–181. 1996.

[12] Mihail Sichitiu Jangeun Jun, Pushkin Peddabachagari. Theoretical maximum throughput of ieee 802.11 and its applications. In *Second IEEE International Symposium on Network Computing and Applications*, pages 16–18, Apr 2003.

[13] Carlos T. Calafate, Pietro Manzoni, Manuael P. Malumbres. Assessing the effectiveness of ieee 802.11e in multi-hop mobile network environments. In *IEEE MASCOTS*, pages 205–212, Oct 2004.