Manuscript Number: WIRE1004R1

Title: On Throughput Guarantee of Aloha-Like Multi-Hop Wireless Networks

Article Type: Manuscript

Keywords: Ad hoc network; Multi-hop; Throughput guarantee; Wireless.

Corresponding Author: Monchai Lertsutthiwong,

Corresponding Author's Institution: Oregon State University

First Author: Monchai Lertsutthiwong

Order of Authors: Monchai Lertsutthiwong; Thinh Nguyen; Alan Fern

Abstract: Providing Quality of Service (QoS) is one of significant issues for multimedia traffic. One approach to achieve the requested QoS is to characterize the traffic flows and guarantee their committed throughput. In a typical multi-hop wireless ad hoc network, determining the feasibility for a given set of flow characteristics is challenging due to the multi-user interference problem. To that end, this paper presents the following contributions. First, we describe a simple Aloha-like Medium Access Control (MAC) protocol that enables each flow to maintain its requested bandwidth, and thus is suitable for multimedia traffic. Second, we propose a bandwidth feasibility algorithm based on the Variable Elimination (VE) technique. The bandwidth feasibility algorithm determines whether or not a given network can support a set of flows of certain bit rates. Simulations indicate that our solution can precisely control the bit rates over all hosts while providing the throughput guarantees.

author's picture & biography

Click here to download author's picture & biography: biography-Monchai-Thinh-Alan.doc

Monchai Lertsutthiwong received the B.E. degree in Telecommunication Engineering from King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand, in 1998 and the M.S. degree in Electrical Engineering from the University of Texas at Arlington (UT-Arlington) in 2004. While at UT-Arlington, he was a recipient of the Texas Telecommunications Engineering Consortium (TxTEC) scholarship. He is currently working toward the Ph.D. degree in Electrical and Computer Engineering at Oregon State University, Corvallis, OR.

His employment experience includes the JVC Manufacturing (Thailand), Samart Communication Services, and Chevron Offshore (Thailand) as an R&D/system engineer during 1998–2002.

He is a member of Eta Kappa Nu and Tau Beta Pi. His research interests include admission control in ad hoc wireless networks, cross-layer optimization, MAC protocol, and scalable video coding.

Thinh Nguyen is an Assistant Professor at the School of Electrical Engineering and Computer Science of the Oregon State University. He received his Ph.D. from the University of California, Berkeley in 2003 and his B.S. degree from the University of Washington in 1995. He has many years of experience working as an engineer for a variety of high tech companies. He has served in many technical program committees. He is an associate editor of the IEEE Transactions on Circuits and Systems for Video Technology, the Peer-to-Peer Networking and Applications. His research interests include Multimedia Networking and Processing, Wireless Networks, and Network Coding.

Alan Fern is an Assistant Professor of Computer Science at Oregon State University. He received his Ph.D (2004) and M.S (2000) in Computer Engineering from Purdue University, and his B.S (1997) in Electrical Engineering from the University of Maine. His research interests span a range of topics in artificial intelligence, including machine learning, data mining, and automated planning/control. He is particularly interested in developing algorithms that leverage rich knowledge representations for learning and discovery in highly structured data.

On Throughput Guarantee of Aloha-Like Multi-Hop Wireless Networks

Monchai Lertsutthiwong, Thinh Nguyen, and Alan Fern
School of Electrical Engineering and Computer Science
Oregon State University, Corvallis, OR 97331, USA
{lertsumo, thinhq, afern}@eecs.oregonstate.edu

Abstract

Providing Quality of Service (QoS) is one of significant issues for multimedia traffic. One approach to achieve the requested QoS is to characterize the traffic flows and guarantee their committed throughput. In a typical multi-hop wireless ad hoc network, determining the feasibility for a given set of flow characteristics is challenging due to the multi-user interference problem. To that end, this paper presents the following contributions. First, we describe a simple Aloha-like Medium Access Control (MAC) protocol that enables each flow to maintain its requested bandwidth, and thus is suitable for multimedia traffic. Second, we propose a bandwidth feasibility algorithm based on the Variable Elimination (VE) technique. The bandwidth feasibility algorithm determines whether or not a given network can support a set of flows of certain bit rates. Simulations indicate that our solution can precisely control the bit rates over all hosts while providing the throughput guarantees.

***Keywords*– Ad hoc network, Multi-hop, Throughput guarantee, Wireless.**

I. Introduction

Recent years have witnessed the rise of wireless ad hoc networking both in research and real-world deployment. A wireless ad hoc network is most useful in places where installing a new communication infrastructure is either expensive or inconvenient to use. In such a network, each wireless host operates not only as a host but also as a router, forwarding packets on behalf of pairs of senders and receivers who are not within their radio ranges. Thus, packets are typically forwarded via multiple hops between the sending and receiving hosts. Consequently, this architecture increases the flexibility of wireless networking at the cost of increased multi-user interference. Therefore, to provide Quality of Service (QoS) for a flow, in such a network, it is imperative to determine the algorithm which takes into account the multi-user interference to accurately model the bandwidth requirement. In particular, providing the throughput guarantee is widely considered as one of the desired criteria for QoS traffic flows.

We note that guaranteeing the throughput is hard, even for a single-hop wireless network such as Wireless Local Area Network (WLAN). In a WLAN, the multi-user interference arises due to the channel contention access, in which the interference or collisions between the packets of the new flow and the existing flows reduce all the flows' throughput. The number of these collisions increases nonlinearly with the number of competing flows, making it more difficult to decide whether or not to admit a new flow based simply on the available bandwidth [1]. On the other hand, the network will accept a new flow if it is able to guarantee that the achievable throughput of all the flows meets the requested requirements.

Furthermore, characterizing the collisions in a multi-hop wireless network is more difficult due to the hidden terminal problem. That said, designing an efficient throughput guarantee algorithm in a multi-hop wireless network is a challenging problem. To mitigate multi-user interference, Medium Access Control (MAC) protocol is used to regulate competition for a shared communication medium among the flows. Thus, characterizing the multi-user interference is specific to a MAC protocol. In this paper, we describe an Aloha-like MAC protocol [2] which enables QoS support for media streams in terms of guaranteeing to achieve its average requested throughput. In particular, this is the first step towards providing throughput guarantee in a multi-hop network with a simple Aloha-like protocol. Using the proposed protocol, we present a bandwidth feasibility algorithm for determining whether or not a network can support a given number of flows, taking into account the multi-user interference. Therefore, the bandwidth feasibility algorithm is used in a novel framework which guarantees the throughput of all flows in a multi-hop wireless network. We note that our framework can be extended to provide the throughput guarantee and admission control algorithm in traditional IEEE 802.11 or other contention-based access networks.

For the ease of analysis, this paper mainly addresses the applications over linear wireless ad hoc networks (e.g., sensor network, railway wayside communication) where all communications require all hosts to be deployed along a line [3],[4]. In a wireless ad hoc sensor network, each sensor wirelessly transmits the detected signal to a centralized control device over a multi-hop route. In railway wayside communication, each mobile wireless device is able to access the internet through other existing devices/repeaters via a pre-defined ad hoc route. However, realistic implementation for a distance wireless connection of existing devices may require a point-to-point connection between them.

We note that our framework can be easily extended to non-linear wireless networks with the expense of higher computational complexities. Thus, our contributions are summarized as follows. First, we describe a simple Aloha-like MAC protocol that enables each flow to maintain its requested bandwidth. This is in contrast with the existing IEEE 802.11 protocols, in which the bandwidth of a flow can fluctuate widely, depending on the number of active flows. Second, we propose a bandwidth feasibility algorithm based on the Variable Elimination (VE) technique which has been used extensively in Artificial Intelligence (AI) and discrete optimization literatures. The bandwidth feasibility algorithm determines whether or not a given network can support a set of flows of certain bit rates. By using the bandwidth feasibility algorithm and the proposed MAC protocol, we guarantee that the solution satisfies all minimum requested bandwidth requirements of all the flows with minimal wasted bandwidth.

II. Preliminaries

A. Related Work

Providing QoS for the flows on wireless contention-based access networks is difficult because each host competes with other hosts for accessing the shared channel. The current design places no limit the number of flows entering the network, or attempt to regulate the bandwidth of individual flows unless admission control algorithm is used. For example, Aad et al. [5] proposed the method to enhancing IEEE 802.11 MAC protocol in congested networks by slowly changing the Contention Window (CW). Similarly, Banchs et al. [6] tuned up the parameters of the IEEE 802.11e in the contention-based mode. When these parameters are set appropriately, this can enable flows to achieve their requested throughputs or reduce the delay. Gao et al. [7] provided the framework by using the long-term average physical rates based scheme in IEEE 802.11e to reserve the channel for some amount of time, called the Transmission Opportunity (TXOP), for each associated host. Furthermore, Bai et al. [8] improved the bandwidth utilization by dynamically changing the transmission time based on the current traffic condition. Pong and Moors [9] proposed the strategy for QoS of flows in IEEE 802.11 by adjusting the CW and TXOP. In all aforementioned works, there is no explicit mechanism to precisely control the bit rates. However, our proposed framework sets right on how to control the bit rates by fine tuning the transmission probability for each host. The detailed discussion for our proposed framework will be discussed in section III.

B. Characteristics of Wireless Networks

Transmissions in wireless networks typically take place in time slots. Often, all the hosts are equipped with a single antenna; as such sending and receiving must be performed in different time slots. Furthermore, all hosts are typically transmitting using the same carrier frequency.

Therefore, a successful transmission from hosts i to j implies that no neighbors of host j other than host i, are transmitting at the same time, otherwise interference would occur at host j.

Centralized scheduling can be employed to coordinate the transmission schedules of all the hosts in the network in order to satisfy the above condition. However, this approach is complex and not scaled to a large network. Therefore, a scalable approach is to allow every host to send its packets opportunistically when a host determines that no other hosts are transmitting. This is the basic framework for the popular IEEE 802.11 protocols. Of course, this approach suffers from several problems. Multiple hosts may decide that no other hosts are transmitting, and thus they all decide to transmit at the same time, resulting in interference. In addition, there is also the hidden terminal problem. The hidden terminal problem arises in the scenario in which the host i can listen to the transmissions of both hosts j and k, but host j cannot listen to the transmission of host k, and vice versa. The problem occurs when both hosts j and k try to transmit to host i at the same time since host j cannot listen to host k's transmission and vice versa. Current WLAN employs IEEE 802.11 protocol to resolve these problems at the expense of some bandwidth overhead. We now first describe the basic of Aloha and IEEE 802.11 protocols. We then present our proposed MAC protocol as a conjunction between those protocols together with a feasibility algorithm to guarantee the requested bandwidth requirements.

C. Aloha Protocol

Contention based access enables multiple hosts to compete for a shared wireless channel. The ALOHA protocol is a MAC protocol for wireless networks with broadcast topology. There are a few remarkable Aloha protocols such as pure Aloha and slotted Aloha protocols. The basic concept of a pure Aloha protocol is described as follows. When a host has data to send, it simply sends out the data to a shared medium. If the data collides with another transmission from other hosts, that host will wait and then re-transmit the data later. We note that pure Aloha has a maximum throughput of about 18.4% of the total available bandwidth. However, there is an improvement to pure Aloha protocol called a slotted Aloha protocol. In a slotted Aloha protocol, we discretize the channel into time slots. Therefore, a host can send only at the beginning of a time slot, and thus collision is reduced. That said, a slotted Aloha protocol provides significant improvement over a pure Aloha protocol. However, these protocols do not have capability to listen to the channel before making a decision to send out the data. Therefore, researchers propose an additional technique called Carrier Sense Multiple Access (CSMA) to avoid such collisions. Note that CSMA is now considered as the standard for typical networks.

D. IEEE 802.11 Protocol

While there are many parameters in contention-based IEEE 802.11 standards, for simplicity we focus our discussion on the CW and TXOP. To access the channel, a host first senses the channel. If the channel is idle for more than the Arbitration Interframe Space (AIFS) time, the host starts sending the data. Otherwise, it sets a backoff timer for a random number of time slots between $[0, CW_{min}]$ where CW_{min} is the minimum contention window size. The backoff timer is decremented by one for each idle time slot after the AIFS time, and halts decrementing when a transmission is detected. The decrementing resumes when the channel is sensed idle again for an AIFS time. A host can begin its transmission for TXOP time slots on the channel as soon as its backoff timer reaches zero. If a collision occurs, i.e., no acknowledgment packet is received after a short period of time, the backoff timer is chosen randomly between $[0, (CW_{min}+1)2^i-1]$ where i is the number of retransmission attempts [10]. In effect, the contention window size is doubled for each retransmission in order to reduce the traffic in a heavily loaded network. By using this procedure, collisions still occur, although less frequently, since each host effectively reduces its transmission rate when there are many active senders.

III. PROPOSED MAC PROTOCOL

One of the main reasons to propose a new MAC protocol is that the current IEEE 802.11 protocols do not support the precise rate control to allocate different bandwidth for different flows. Instead, every flow in the current IEEE 802.11b protocol has the same priority and consumes more or less the same amount of bandwidth under similar network conditions. There have been the work to provide the service differentiation of the flows in IEEE 802.11 networks by tuning the values of CW_{min} and TXOP [11] for each flow. A detailed survey of existing MAC scheme for traffic differentiation can be found in [12]. We note that the recent IEEE 802.11e standard has capability to tune up those parameters [13]. However, the service differentiation only guarantees that a flow belonging to one type can obtain larger bandwidth than those of other types, rather than providing a specified bandwidth for a flow.

The idea to control the average bit rate of individual flows is simple. Rather than doubling the contention window size of a flow after a collision is detected, every flow maintains a fixed window size unless it is told to change explicitly by the throughput guarantee algorithm. We note that doubling the contention window size makes sense when such algorithm is not employed in the network. Thus every host must reduce its rate corresponding to an increased traffic load in order to avoid collisions. We argue that when a proper throughput guarantee algorithm is employed, eliminating this doubling of the contention window size helps to increase the bandwidth efficiency by not reducing the sending rate of each flow unnecessarily.

For simplicity to analyze our proposed MAC protocol, similar to a slotted Aloha MAC protocol, we do not employ the RTS/CTS packets to reserve the channel before sending data. Each host arbitrarily sends packets with some transmission probability p. That said, p is the probability for transmitting a packet given that the host has a packet to send out to its neighbor in the current time slot. Note that, for each packet, the host transmits it until the first success meets which is the characteristic of the geometric distribution. Therefore, the time taken for each host to access the shared channel is a geometrically distributed random variable with parameter p. Thus, the effective transmission rate of a host depends on the frequency of sending packets, i.e., p, and their successful percentage. Furthermore, setting appropriate values of p_i's for each host i is a way to precisely control the transmission rates of different flows. To translate the transmission probability p back to the contention window CW used in IEEE 802.11 protocols, Bianchi [14] extensively analyzed the performance of IEEE 802.11 and showed that CW can be approximately set to $2/p - 1 \approx 2/p$. This is only an approximation since CW in IEEE 802.11 protocols is not reset at every time slot. Note that our proposed protocol is intentionally designed for contention-based access networks. Therefore, in the case of multi-mode devices (e.g., CDMA/OFDMA), we may apply our protocol to the situation where the bandwidth is not sufficient for all requested throughputs and multiple hosts need to compete each other in order to access the shared channel. Thus, for computing probabilities p's, we require one host to perform this computation.

To that end, a throughput guarantee algorithm based on the proposed MAC protocol needs to accurately answer the question: *Given a number of flows with specified rates in a wireless network, is there a set of transmission probabilities p_i for each host i involved in the transmissions, such that all the specified rates are achievable?* In the next section, we describe such an algorithm.

IV. Feasibility Algorithm

We first formally describe a wireless ad hoc network as a graph $G(V, E)$ with a set of vertices V and a set of edges E. Each vertex $v_i \in V$ represents a host i in the network. An edge e_{ij} between vertices v_i and v_j exists if and only if hosts i and j can listen to each other's transmissions. We assume that all hosts use the same underlying transmission technology with a fixed known transmission capacity, e.g., 54 Mbps for IEEE 802.11g networks. Using the proposed MAC protocol in Section III, a host i transmits a packet with probability p_i when it has a packet to send out to its neighbor.

To accurately determine whether or not a given network can support a specified number of flows with the corresponding rates, we assume that the proposed feasibility algorithm has full knowledge of the network; including the network topology, the routes of all the flows, and their corresponding rates. We implicitly assume that the routes taken by the flows are established previously by some routing protocol. These assumptions are unrealistic for a large network with many active flows which requires a significant book-keeping effort. On the other hand, for a smaller network, this approach is feasible. We hypothesize that a reasonably accurate feasibility algorithm can be implemented without the full knowledge of such a network. However, the emphasis of this paper is on the theoretical aspects of the algorithm rather than its implementation. Thus, we will discuss the feasibility of the proposed algorithms with respect to the characteristics of network topologies.

To successfully maintain an average requested bit rate of a flow, it is necessary that each link (edge) in a path connecting the source and the destination is able to support the requested bit rate. To determine the bandwidth between two hosts, we must model the transmission behaviors of associated neighbors of those two hosts in order to take into account the multi-user interference. To that end, a successful transmission from a sender directly to a receiver implies that no neighbor of the receiver or the receiver is transmitting a packet when the sender is transmitting a packet. Otherwise, the packet transmitted by the sender will be collided at the receiver.

We note that the scope of this paper is mainly for a linear wireless ad hoc network logically similar to a chain topology where all communications require all hosts to be deployed along a line. However, this framework can be applied to other network types with higher computational

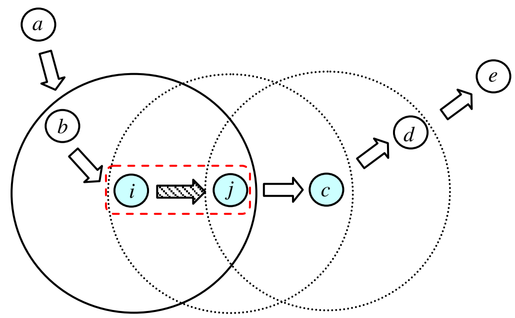


Fig. 1. A simple subnetwork ad hoc model when host i intends to send the packets to its neighbor j. We need to take into account hosts i, j, and c for successfully transmitting packets from host i to host j.

complexities. Therefore, as an example, a linear wireless ad hoc network is depicted in Fig. 1 where each large arrow represents a flow on a particular link and the circle represents the transmission ranges. In particular, the transmission from hosts i to j is successful if none of hosts c and j is transmitting packets in the same time slot. Note that transmission from either hosts d or e will not affect transmission from hosts i to j due to parallel transmission property [15]. In particular, the radio ranges from hosts d or e do not reach to a host j. As a result for the transmission from hosts i to j, we need to take into account all associated hosts $v \in \{j, N(j)\}$ where $N(j)$ represents the neighbors of host j.

Therefore we can formulate the equations representing wireless behaviors of ad hoc hosts over an entire network, specified by giving: R_i is the total outgoing throughput from host i; R_{ij} is the outgoing throughput from hosts i to j; p_i is the transmission probability that host i sends a packet; and S_{ij} is the percentage of successfully transmitting packets from hosts i to j.

The relationship between R_i and R_{ij} is that $R_i = \sum_{j \in N_I(i)} R_{ij}$ where $N_I(i)$ is the neighbor of host i that host i intends to send the packets to. Therefore, the fractional throughput from hosts i to j over total outgoing throughput from host i is $\theta_{ij} = R_{ij}/R_i$. That is,

$$\theta_{ij} p_i \prod_{v} (1 - p_v) \quad \geq \quad S_{ij} \tag{1}$$

where $v \in \{j, N(j) \backslash i\}$. The solution exists if (1) is achievable.

Note that the percentage of successfully transmitting packets S_{ij} can be represented by (2) where the maximum payload size of each packet for every host is equal to the transmission opportunity (TXOP); the number of packets we need to transmit for the required throughput R_{ij} is $\lceil R_{ij}/TXOP \rceil$; and the size of channel capacity is BW. Recall that we consider the channel into time slots. For simplicity of analysis, we assume one time slot is equal to $TXOP$. Each packet contains only a payload without PHY or MAC overhead portions. That is,

$$\begin{aligned} S_{ij} &= \frac{\text{number of packets for } R_{ij}}{\text{channel capacity}} \\ &= \frac{\left\lceil \frac{R_{ij}}{TXOP} \right\rceil}{BW} \end{aligned} \tag{2}$$

Finally, we can formulate the potential function $f_{i \to j}$ to send packets from hosts i to j as shown in (3).

Function $f_{i \to j}$

$$= \begin{cases} 1 & ; \text{if } \theta_{ij} p_i \prod_v (1 - p_v) \quad \geq \quad S_{ij} \\ 0 & ; \text{otherwise} \end{cases} \tag{3}$$

where $v \in \{j, N(j) \backslash i\}$ and $0 < S_{ij} \leq 1$. We note that the result computed for one subnetwork is not a solution for an entire network containing a number of subnetworks. Assume there are n active hosts. Therefore, the solution for an entire network exists if the result computed by (4) is greater than zero. That is,

$$\max_{p_1, p_2, \ldots, p_n} \prod_{(i,j)} f_{i \to j} \prod_i (1 - p_i) \tag{4}$$

where i = 1,2,...,n and $j \in N_I(i)$. The product of $f_{i \to j}$ returns a set of solutions to achieve all desired throughput requirements. In order to avoid unnecessarily transmitted packets due to assigning unnecessarily high transmission probabilities to everyone, we use the product of $(1 - p_i)$ together with maximizing the final computation. Thus, this technique would provide us a solution with minimal collisions.

Note that when a number of wireless hosts are close to each other, a linear wireless network turns into a non-linear wireless network. This is because the transmission range of one host covers a number of surrounding hosts considered as its neighbors. By using a feasibility algorithm, the computational complexity relies on all neighbors of considered wireless host where we intend to transmit the packet to. Thus, our framework may not be suitable for a large network with high density of wireless hosts. Therefore, based on our assumptions over the implementation aspects, our proposed protocol is able to operate in practice if we know all of the requested

Pseudocode for a generic variable elimination

x_i := an assigned value to a variable X_i
π := an elimination ordering (assume $\{ x_1, x_2, x_3,..., x_i,..., x_n \}$)
Φ := a product of all the functions
Φ_{x_i} := a new function where variable x_i was eliminated
Ω := a set of optimal solutions for all variables
for each variable x_i in π **do**
  remove all functions containing x_i from Φ then multiply those removed functions to form a potential function Φ_{x_i}
  create a table for Φ_{x_i}. Each entry (in the same row) contains a set of all possible combinations of all variables in Φ_{x_i} except x_i together with the best x_i that maximizes Φ_{x_i}. Then return $argmax_{x_i}\ \Phi_{x_i}$
for each variable x_i in reverse order of π **do**
  if x_j is variable in Φ_{x_i}
    Search for optimal value x_j^* in Ω then substitute the value of x_j in Φ_{x_i} with x_j^*
    Find x_i^* that maximizes Φ_{x_i} then record x_i^* in Ω
return $\Omega = \{ x_1^*, x_2^*, x_3^*,\ldots, x_i^*,..., x_n^* \}$

Fig. 2. Pseudocode for a variable elimination technique.

throughputs, network topologies, and channel conditions. This implies that our protocol provides high efficiency if we operate under some certain conditions.

V. Variable elimination technique

To determine a solution for multiple variables, one option is to employ a useful technique called Variable Elimination (VE). This technique [16] multiplies all given potential functions (each composed of at least one variable) to achieve an overall function. Clearly, an overall function gathers the properties from all variables. VE technique eliminates one variable at a time by replacing a product of all functions containing that variable with a single function. In particular, if we are eliminating a variable X_i with an assigned value of x_i, a product of all functions containing x_i becomes a new function Φ_{x_i} which does not contain x_i. Note that a VE technique requires knowing the range of possible solutions for all variables. Once we know the range, we discretize it into multiple bins. When we create Φ_{x_i}, we will generate a table containing the results for all possible combinations for all variables in Φ_{x_i} except x_i. In other words, each of possible combinations in Φ_{x_i} would keep the best x_i maximizing Φ_{x_i}. Once we eliminate all variables, we are now able to optimally determine the solution for each variable in

Let $\pi = \{p_1, p_2, p_3\}$

$$\max_{p_1,p_2,p_3} p_1 \cdot (1 - p_1 p_2) \cdot (1 - p_2 p_3)$$
$$= \max_{p_2,p_3} \Phi_1(p_2) \cdot (1 - p_2 p_3)$$
$$= \max_{p_3} \Phi_2(p_3)$$

where $\Phi_1(p_2) = \max_{p_1} p_1 \cdot (1 - p_1 p_2)$

$\Phi_2(p_3) = \max_{p_2} \Phi_1(p_2) \cdot (1 - p_2 p_3)$

$\phi_1(p_2) = \arg\max_{p_1} p_1 \cdot (1 - p_1 p_2)$

$\phi_2(p_3) = \arg\max_{p_2} \Phi_1(p_2) \cdot (1 - p_2 p_3)$

Then $p_3^* = \arg\max_{p_3} \Phi_2(p_3) = 0.3$

$p_2^* = \phi_2(p_3^*) = 0.3$

$p_1^* = \phi_1(p_2^*) = 0.9$

Finally, $\Omega = \{p_1^*, p_2^*, p_3^*\} = \{0.9, 0.3, 0.3\}$

p_2	p_1	$p_1(1-p_1p_2)$
0.3	0.3	0.273
	0.6	0.492
	0.9	0.657
0.6	0.3	0.246
	0.6	0.384
	0.9	0.414
0.9	0.3	0.219
	0.6	0.276
	0.9	0.171

p_2	$\Phi_1(p_2)$	p_1^*
0.3	0.657	0.9
0.6	0.414	0.9
0.9	0.276	0.6

p_3	p_2	$\Phi_1(p_2)\cdot(1-p_2p_3)$
0.3	0.3	0.598
	0.6	0.340
	0.9	0.201
0.6	0.3	0.539
	0.6	0.265
	0.9	0.127
0.9	0.3	0.480
	0.6	0.190
	0.9	0.052

P_3	$\Phi_2(p_3)$	P_2^*
0.3	0.598	0.3
0.6	0.539	0.3
0.9	0.480	0.3

Fig. 3. Example for a variable elimination technique.

reverse elimination ordering. Finally, the pseudocode for a VE technique is shown in Fig. 2.

For a concrete example as shown in Fig. 3, we have three variables (i.e., p_1, p_2, p_3) with the possible values of $\{0.3, 0.6, 0.9\}$. We have been asked to maximize $\Phi = p_1(1 - p_1p_2)(1 - p_2p_3)$ over p_1, p_2, and p_3. Assume an elimination ordering $\pi = \{p_1, p_2, p_3\}$. First, we eliminate p_1 by creating a table for a product of all terms containing p_1, which is $p_1(1 - p_1p_2)$. Second, we create a table for $\Phi_1(p_2)$ that contains the best p_1 for each possible value of p_2 such that $\Phi_1(p_2) = \max_{p_1} p_1(1 - p_1p_2)$. On the other hand, $\phi_1(p_2) = \arg\max_{p_1} p_1(1 - p_1p_2)$ returns the best p_1 for any given value of p_2. Next, recursively compute for $\Phi_2(p_3)$. Note that we first get the optimal value of p_3, denoted by p_3^*. Then, we compute $p_2^* = \phi_2(p_3^*)$ and $p_1^* = \phi_1(p_2^*)$, respectively. Finally, we have a set of optimal solution $\Omega = \{p_1^*, p_2^*, p_3^*\}$ to maximize Φ over p_1, p_2, and p_3.

Consider the computational complexity where we need to determine a solution for n variables. Note that the theoretical computational cost of our proposed protocol depends on type of network topologies, feasibility algorithm, and VE technique. Because we may not be able to control network topologies in practice and the performance of feasibility algorithms relies on VE techniques, therefore, the computational cost of the system strictly depends on the VE performance.

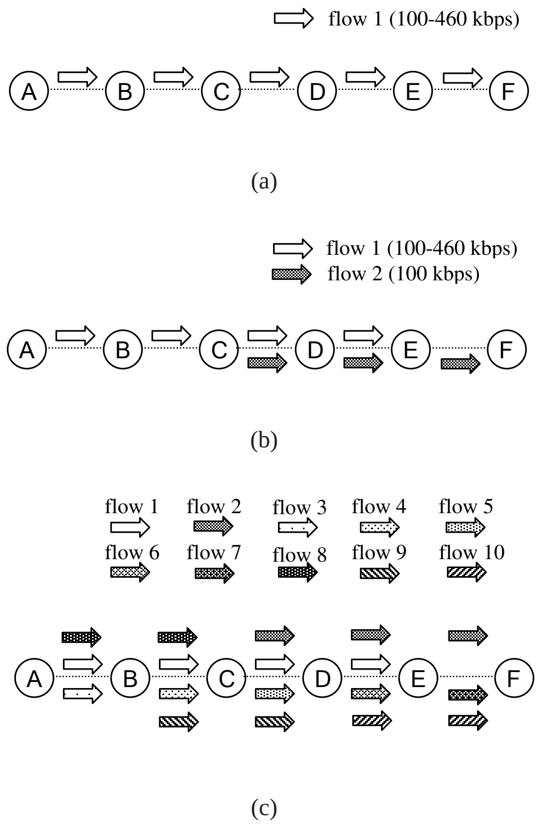


Fig. 4. Example for a linear wireless ad hoc network. (a) Network with one flow; (b) Network with two flows; (c) Network with ten flows.

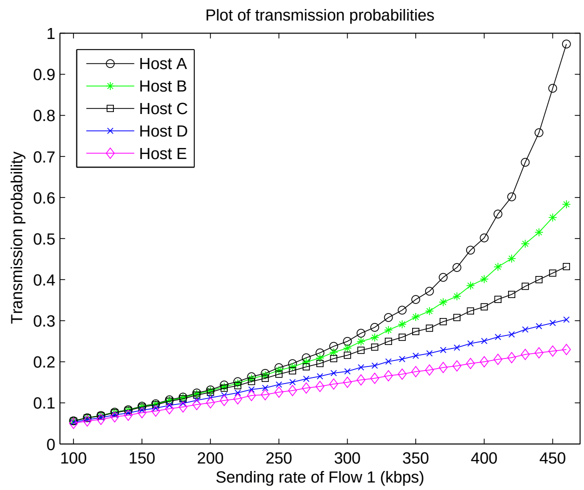
Clearly, the problem becomes hard if the order of polynomial equations is high and there are so many variables in the system. Fortunately, each host in a multi-hop ad hoc network gets involved with only its nearby neighbors. Therefore, the number of variables in each potential function depends on the number of its nearby neighbors where the variable here is the transmission probability p_i for each host i. Together with the VE technique, the complexity in each iteration where we intend to eliminate the variable p_i is proportional to the number of all variables over all the functions containing p_i. In particular, if host i gets involved with other α hosts and the possible values in each host are discretized into ϵ bins, then the computational complexity is $O(\epsilon^\alpha)$, compared to $O(\epsilon^n)$ where $\alpha \ll n$ for a large network. Thus, for example in Fig. 3, the computational costs are $O(\epsilon^2)$ and $O(\epsilon^3)$ for computations with and without the VE technique, respectively.

VI. Simulations and experimental results

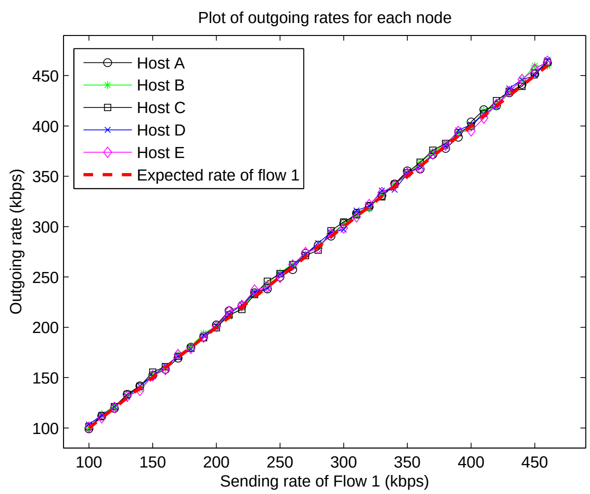
We have the experimental results based on a linear wireless ad hoc network topology as shown in Fig. 4. The dash line represents the wireless connection between hosts. On the other hand, it shows the coverage area from one host to its neighbors. The maximum bandwidth, TXOP, and time slot size are 2 Mbps, 500 bytes, and 500 bytes, respectively. To be fair among all flows (also hosts), they use the same TXOP. We discretize the transmission probability from zero to one with step size of 0.004. For simplicity of analysis, we have the assumptions as follows: no PHY/MAC overhead in each packet; no acknowledgement packet (ACK) when the receiver successfully receives the sent packet; when a packet gets lost, the sender simply retransmits that packet; because this is an Aloha-like MAC protocol, we do not consider Short Interframe Space (SIFS) and DCF Interframe Space (DIFS) as in IEEE 802.11 [10].

At this point, we evaluate our proposed framework by using the network topology as shown in Fig. 4(a). Assume flow 1 (from host A to host F) linearly increases its outgoing rate from 100 kbps to 460 kbps with increased rate of 10 kbps per iteration. Therefore, all senders (hosts A-E) have the same desired outgoing rates. The simulation results are shown in Fig. 5 which we averaged out over 200 runs for each iteration. The transmission probabilities for all senders (hosts A-E) are shown in Fig. 5(a). As expected for a linear network topology with one traffic flow, the host closer to an origin of the flow has higher transmission probability than the host further away from an origin. On the other hand, the last-hop sender would have the lowest transmission probability because its transmission is always successfully received by the destination. Therefore, transmission probability for a host E would be minimal compared to those for other hosts in this network. The outgoing (throughput) rates of all senders are shown in Fig. 5(b). We show that our novel framework precisely controls the outgoing rates of all senders.

To verify that our proposed protocol is not limited to a one-flow network, we setup the network topology with two flows as shown in Fig. 4(b). We linearly increase the outgoing rate of flow 1 (from hosts A to E) from 100 kbps to 460 kbps with increased rate of 10 kbps per iteration. The outgoing rate for flow 2 (from host C to host F) is constant at 100 kbps. In this example, both flows have the same direction. The corresponding results for transmission probabilities are shown in Fig. 6(a). Regardless of the number of flows in the network, our framework always precisely controls the rate with minimal deviation as shown in Fig. 6(b) if there exists the solution.



(a)

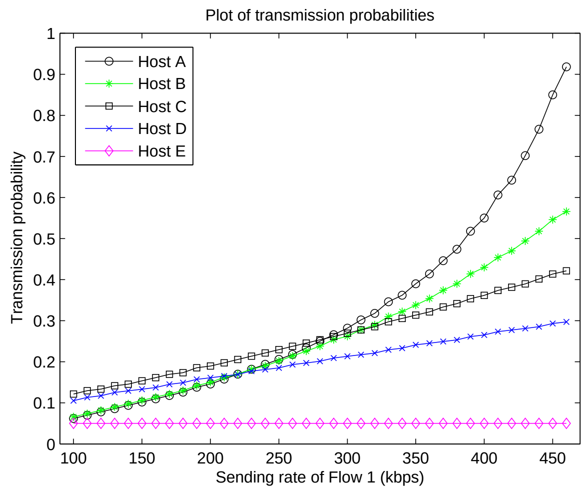


(b)

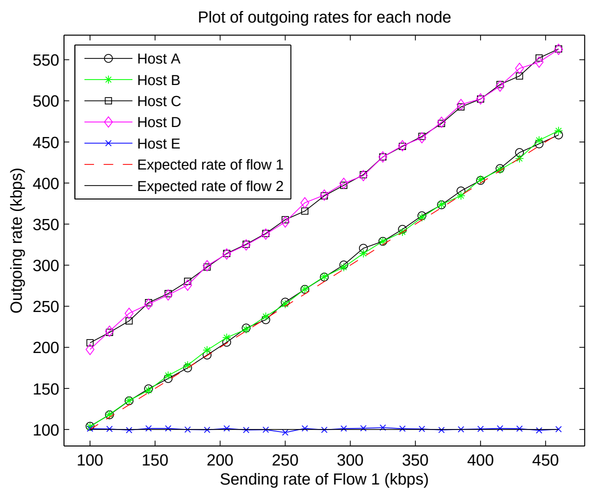
Fig. 5. The outgoing rates from each sender based on a network topology as shown in Fig. 4(a). (a) Transmission probabilities; (b) Outgoing rates

For concrete results, we show the degree of scalability of our proposed protocol with 10 flows over the network topology as shown in Fig. 4(c). The transmission rates for flows 1-10 are 100, 300, 30, 40, 50, 60, 70, 80, 90, and 100 kbps, respectively. The corresponding results are represented in Table I. Note that our protocol guarantees the achievable throughput about 99.98% compared to expected throughput.

We note again that even though it is possible to have more than one solution, our proposed technique is able to provide a solution with minimal value of transmission probabilities based on



(a)



(b)

Fig. 6. The outgoing rates from each sender based on a network topology as shown in Fig. 4(b). (a) Transmission probabilities; (b) Outgoing rates

(4). Furthermore, smaller step size of transmission probabilities would provide a better solution in terms of higher accuracy to control the outgoing rates of the hosts but computational cost is more expensive. Therefore, this framework is able to be applied for applications requiring less fluctuation in achievable throughput, especially for multimedia streaming.

TABLE I

PERFORMANCE OF OUR PROPOSED FRAMEWORK BASED ON A NETWORK TOPOLOGY AS SHOWN IN FIG. 4(C)

	Expected outgoing rate (kbps)	**T**ransmission probability	**A**ccuracy (%)
host A	210	0.700	99.8861
host B	310	0.600	99.8931
host C	540	0.565	99.8992
host D	560	0.370	99.8993
host E	470	0.240	99.8986

VII. CONCLUSIONS

In this paper, we propose an Aloha-like MAC protocol which enables QoS support for media streams in terms of guaranteeing to achieve its requested bandwidth. This is in contrast with the existing IEEE 802.11 protocols in which the bandwidth of a flow can fluctuate widely, depending on the number of active flows. Then, we propose a bandwidth feasibility algorithm based on Variable Elimination technique. By using the bandwidth feasibility algorithm together with a proposed MAC protocol, we are able to determine the solution (if one exists) to meet all requirements for a given network while providing minimal wasted bandwidth caused by multi-user interference. We note that this is the first step towards providing throughput guarantee in a multi-hop network. Furthermore, our framework is not limited to operate under a simple Aloha-like network but this also can be extended to provide the throughput guarantee and admission control algorithm in traditional IEEE 802.11 or other contention-based access networks with minimal modification. Our simulations indicate that the proposed framework is able to precisely control the achievable throughput for every host within 1% deviation from requested requirements while providing the throughput guarantee.

REFERENCES

[1] M. Ergen and P. Varaiya, “Throughput analysis and admission control for ieee 802.11a,” *Mobile Networks and Applications 10*, pp. 705–716, 2005.

[2] T. Nguyen, K. Nguyen, and L. He, “Collaborative distributed admission control (cdac) for wireless networks,” *CDS*, p. 75, Jun. 2007.

[3] K. Hellman and M. Colagrosso, “Investigating a wireless sensor network optimal lifetime solution for linear topologies,” *Journal of Interconnection Networks*, vol. 7, pp. 91–99, 2006.

[4] *http://www.afar.net/technology/linear-network/*.

[5] I. Aad, Q. Ni, C. Castelluccia, and T. Turletti, “Enhancing ieee 802.11 performance with slow cw decrease,” *IEEE 802.11e working group document*, Nov. 2002.

[6] A. Banchs, X. Perez-Costa, and D. Qiao, “Providing throughput guarantees in ieee 802.11e wireless lans,” *18th International teletraffic congress*, Sep. 2003.

[7] D. Gao, J. Cai, and K. N. Ngan, “Admission control in ieee 802.11e wireless lans,” *IEEE network*, vol. 19, pp. 6–13, Jul. 2005.

[8] A. Bai, B. Selvig, T. Skeie, and P. Engelstad, “A class based dynamic admitted time limit admission control algorithm for 802.11e edca,” in *6th International workshop on applications and services in wireless networks*, Berlin, Germany, May 2006.

[9] D. Pong and T. Moor, “Call admission control for ieee 802.11 contention access mechanism,” *GLOBECOM*, vol. 1, pp. 174–178, Dec. 2003.

[10] *IEEE 802.11: Wireless LAN medium access control (MAC) and physical later (PHY) specifications*, IEEE Std., 1999.

[11] A. Lindgren, A. Almquist, and O. Schelen, “Evaluation of quality of service schemes for ieee 802.11,” pp. 348–351, Nov. 2001.

[12] H. Zhu, M. Li, I. Chlamatac, and B.Prabhakaran, “Survey of quality of service in ieee 802.11 networks,” *IEEE wireless comm.*, vol. 11, pp. 6–14, Aug. 2004.

[13] *IEEE 802.11e: Wireless LAN medium access control (MAC) and physical later (PHY) specifications*, IEEE Std., 2005.

[14] G. Bianchi, “Performance analysis of the ieee 802.11 distributed coordination function,” *IEEE journal in communications*, vol. 18, pp. 535–547, Mar. 2000.

[15] Y. Tay and K. Chua, “A capacity analysis for the ieee 802.11 mac protocol,” *Wireless Networks*, vol. 7, pp. 159–171, Mar. 2001.

[16] D. Poole, A. Mackworth, and R. Goebel, *Computational Intelligence: A Logical Approach*. Oxford University Press, 1998.