Peer-to-Peer Communication in Wireless Local Area Networks

Mort Naraghi-Pour
Dept. of ECE
Louisiana State Univ.
Baton Rouge, LA 70810

Manju Hegde
Dept. of EE
Washington Univ.
St. Louis, MO 63130

Ramesh Pallapotu
COMSEARCH
2002 E. Halley Dr.
Reston, VA 20191

Corresponding author: Mort Naraghi-Pour
E-mail: mort@ee.lsu.edu Ph: (504) 388-5551 FAX: (504) 388-5200

Abstract

A new MAC protocol which supports peer-to-peer direct communication is introduced for a packet switched wireless network. Terminals that are located within range of each other and are sufficiently isolated from the base station can communicate with their peers directly without the use of the base station as a relay. Slotted Aloha is used as the access protocol. Throughput and delay of the protocol are evaluated. Numerical results are presented which show that significant improvements in throughput/delay performance can be obtained over a system using slotted Aloha without peer-to-peer communication.

Index Terms— Wireless LAN, MAC protocol, peer-to-peer communication, slotted Aloha, throughput and delay.

1 Introduction

Interconnection of data terminals to LAN's by means of wireless links allows for flexible location of these terminals, thus eliminating the need for wiring when terminals are added, removed or relocated. Furthermore, the mobility offered by such systems is highly desirable in applications such as inventory control in warehouses, car rental checkins and hospital and university environments. As a result recent years have witnessed a rapid development of wireless local area networks (WLAN's) [9] [11] [12] [13].

In a WLAN a number of terminals transmit packets on a shared radio channel whose bandwidth is often fairly limited. Therefore, an efficient media access control (MAC) protocol is needed to regulate the transmission of packets by different terminals on the shared channel. To this end, several wireless MAC protocols have been recently proposed and evaluated. See for example [2] [3] [5] [6] [7] [8] [9] and the references in [9].

In this paper we present a MAC protocol for WLAN's which supports peer-to-peer direct communication. We consider a packet switched architecture in which a geographic area is divided into cells. Each cell is served by a base station which acts as the coordinator and an access point for the terminals (nodes) in that cell. The base stations are connected to some backbone network which enables terminals to communicate with their peers located either on the wired network or in some other cell. The terminals within a cell communicate with their peers in one of two ways. When two terminals are far from each other they communicate by establishing a wireless link through the base station. They transmit their packets to the base station which then relays the packets to their peer. Alternatively, if the terminals are located close to each other, the MAC protocol allows them to communicate directly on a peer-to-peer basis without the use of the base station. When two terminals that communicate through the base station move close to each other they tear down the existing link and establish a direct peer-to-peer link. Similarly, when two peers which communicate directly move apart or the quality of the link deteriorates, they tear down the direct link and establish a link through the base station. Terminals located in different cells communicate through their respective base stations and the backbone network.

Allowing for direct peer-to-peer communication results in a considerable reduction of interference to other terminals and a significant saving of power for the terminals. Furthermore, direct peer-to-peer communication reduces the number of contenders who want to transmit to the base station resulting in improved throughput and delay. The protocol is well suited to an indoor environment, such as an easily reconfigurable desktop environment where the mobility of terminals is limited. Such an environment provides considerable spatial isolation due to the presence of walls and other physical obstructions.

The remainder of this paper is organized as follows. In Section 2 we describe the MAC protocol. In Sections 3 and 4 we evaluate the throughput and delay for the uplink and the downlink channels, respectively. Numerical results are presented in Section 5. Finally, in Section 6 we present our conclusions.

2 MAC Protocol

The uplink and the downlink channels are assumed to be separated using frequency division duplexing (FDD). Signaling and control information are transmitted through a third low-bandwidth channel. (Note that this channel configuration is the same as that in slotted Aloha and therefore no additional bandwidth is required by this protocol over that of slotted Aloha protocol.) Time is slotted so that each packet's transmission time is exactly one slot and all the nodes are synchronized so that transmissions occur within slot boundaries. The base station along with terminals communicating with it is referred to as *subnetwork* 0 and peer-to-peer communicating pair (A_i, B_i) is referred to as *subnetwork* i.

The uplink channel is used in a contention mode by the terminals that communicate with the base station as well as the terminals, A_i, communicating directly with their peers. In order to keep the interference at the base station caused by the peer-to-peer communicating terminals low, peer-to-peer communication is restricted to terminals that are within range of each other and are sufficiently isolated from the base station. (In the case of outdoor cells, we can divide the cell into two concentric zones and restrict peer-to-peer communication to the outer zone only.) This prohibits direct communication in the vicinity of the base station and increases the propagation distance and thereby the path loss between the base station and the terminals utilizing the uplink channel for direct communication.

The slotted Aloha protocol [4] is used for transmission on the uplink channel. A terminal with a new packet to transmit waits for the next time slot to transmit the packet. A *collision* occurs at the receiver if more than one packet is transmitted in the same slot. At the end of the slot the intended receiver transmits a feedback to indicate if the packet was successfully received or not. A terminal whose packet was involved in a collision is *backlogged*. This terminal will retransmit the packet in subsequent slots with a certain retransmission probability until the packet is successfully received at the receiver.

On the downlink channel the slots are grouped into a fixed frame structure with T slots per frame. Of these, $T - s$ slots are reserved for the base station (the BS period) and the remaining s slots are reserved for terminals communicating directly with their peers (the P-P period).

The base station receives packets destined for terminals in the cell either from the wired network or from other terminals of subnetwork 0. These packets are broadcast on the downlink channel in the BS period to all the terminals. Upon examining the headers of the packets received on the downlink channel the terminals determine if the packet is intended for them.

In the P-P period the base station remains silent and the peer-to-peer terminal B_i transmits its packets directly to A_i using slotted Aloha. Collisions may occur at A_i with packets transmitted by other terminals transmitting on the downlink channel. Terminals whose packets are involved in a collision are informed via feedback from their peers and will attempt retransmissions in subsequent slots with a certain retransmission probability until the packet is received correctly.

Connection establishment Connection requests generated by terminals are sent to the BS on the signaling channel. The request specifies the network addresses of the two end-points. The BS determines if the two end-points are located within the same cell. If not, the request is sent to the switching center on the backbone network. Otherwise, the BS processes the request to determine whether direct communication can be set up. This requires that the two peers be within range of each other and that they not be located in close proximity to the base station. If these two conditions are satisfied the base station informs the peers and direct communication is set up. In order to verify these conditions, the base station has to maintain a database of the location of each terminal. In the case of very low terminal mobility (which we assume) the overhead associated with this database maintenance is not significant.

Signaling channel The base station uses the signaling channel to transmit control signals such as the clock which is needed for synchronization of the terminals to the slot boundaries, the acknowledgment after the end of each time slot which indicates whether a packet transmitted on the uplink channel is correctly received by the base station, the beginning and end of the P-P period and the call setup message indicating whether the call is peer-to-peer or through the base station.

Fig. 1 shows the slot structure on the uplink channel, the downlink channel as well as the various control signals on the signaling channel.

Subnetwork acknowledgments (ACKs) At the end of each time slot, the peer-to-peer terminals have to transmit feedback to their peers to indicate the outcome of packet reception in that slot. A small end portion of the time slot on the uplink and the downlink channels is divided into K_{max} mini-slots in which terminals transmit their feedback. K_{max} denotes the maximum number of peer-to-peer communicating terminal pairs allowed in a cell. Each terminal transmitting on a peer-to-peer basis is allotted one of the K_{max} mini-slots to transmit its feedback to its peer. The base station reserves the mini-slots (on the uplink and the downlink channels) for each peer-to-peer subnetwork and informs the terminals at the time of direct connection set up. Fig. 1 shows these mini-slots on the uplink and downlink channels. We assume that all acknowledgments are received error free.

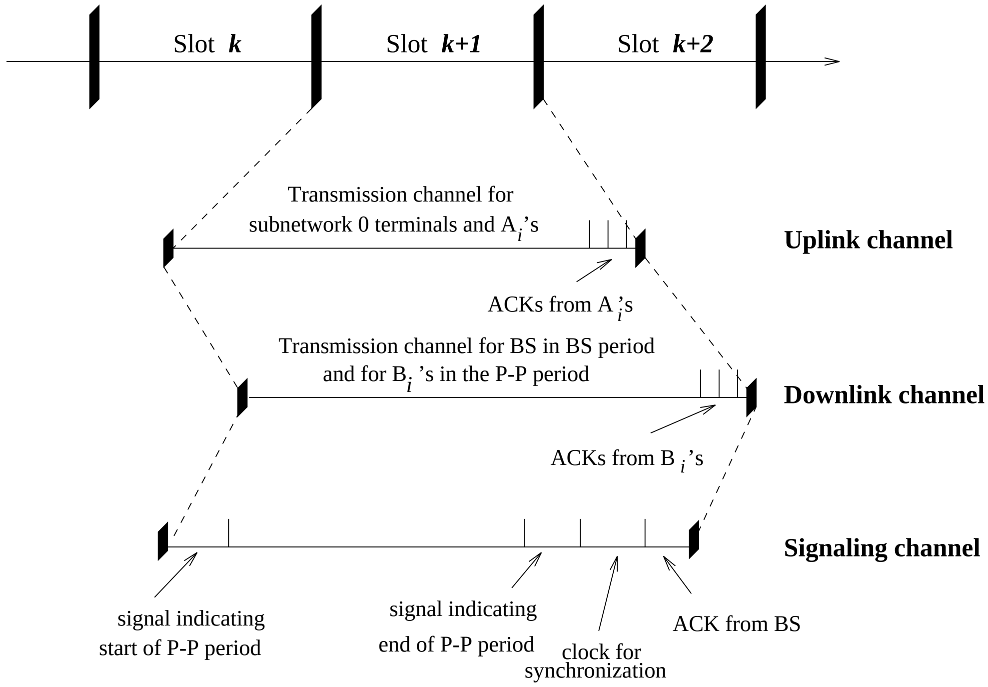

Figure 1: Slot structure and timing diagram.

Power control In order to mitigate interference caused to other subnetworks and to reduce power consumption, peer-to-peer communicating terminals use a simple power control algorithm.

When the connection is initially set up the power is set to the maximum value allowed for direct communication. Then, based on the quality of the received signal, a power control bit is set by the receiver and sent along with the ACK. Based on these bits the transmitter adjusts its transmit power. Thus on the average peer-to-peer communication is conducted at lower power levels than that between base station and terminals. In fact, as mentioned previously, the configurations under which peer-to-peer communication are permitted are chosen so as not to cause interference at the base station.

3 Throughput and Delay on the Uplink channel

In this section we evaluate the throughput and delay of the MAC protocol on the uplink channel. We consider a system with m terminals communicating with the base station and K peer-to-peer communicating pairs (A_i, B_i), $i = 1, 2, ..., K$. Packets are generated at unbacklogged terminals according to independent Bernoulli processes with probability p_0 that a packet arrives in a given slot. Backlogged terminals of subnetwork 0 retransmit packets with probability q_r and backlogged terminals of other subnetworks retransmit packets with probability q_r'. It is assumed that all terminals use the immediate first transmission policy of slotted Aloha, i.e., a packet is transmitted with probability one in the first slot after its arrival [4]. It is further assumed that the terminals have a single buffer, so new packets generated at a terminal which has a packet to transmit are discarded ([2], [4], [6]).

3.1 Uplink throughput

Assume that for $i = 1, 2, ..., K$, terminal A_i uses the uplink channel to transmit to B_i. Let Th_i denote the throughput of the ith subnetwork on the uplink channel. Then the throughput of the network on the uplink channel is given by $S^{(u)} = \sum_{i=0}^{K} Th_i$. We evaluate Th_i for $i = 0, 1, ..., K$.

Since terminals communicating on a peer-to-peer basis are isolated from the base station and since they transmit with low power, these terminals do not cause any collisions at the base station. Therefore, for $j = 0$, Th_j is the throughput of the slotted Aloha system, [4], and is given by $Th_0 = \sum_n P_{succ}(n)\pi_n$, where $P_{succ}(n)$ is the probability that in a given slot a successful transmission takes place when n nodes (out of m) are backlogged and π_n is the steady state probability that n nodes are backlogged. Both $P_{succ}(n)$ and π_n can be evaluated from the transition probabilities of a Markov chain whose state represents the number of backlogged nodes (see [4], pp. 277-282).

We now evaluate Th_i for $i \neq 0$. Let $H(i)$ denote the set of terminals that can be heard by B_i. Let $V(i)$ denote the subset of terminals in subnetwork 0 that can be heard by B_i and let $U(i) = H(i) - V(i)$. $U(i)$ is the set of interferers communicating on a peer-to-peer basis that can be heard by B_i. For $j \neq i$ consider the event that in a given slot, a transmitting node $A_j \in U(i)$ is heard at B_i. We assume that this event is independent of all other preceding and current events in the network and (given that A_j transmits in a given slot) has a fixed (conditional) probability $\varphi_{j,i}$. The matrix $\Phi = [\phi_{i,j}]$ is referred to as the interference matrix on the uplink channel. Similarly, consider the event that a transmitting node $C_j \in V(i)$ is heard by B_i. We assume that this event too is independent of all other preceding and current events in the network. Since these terminals transmit with a higher power than terminals that communicate on a peer-to-peer basis, we assume the same probability for all these events. In other words we assume that the (conditional) probability that any terminal B_i, $i = 1, 2, ..., K$, hears a transmission from any terminal $C_j \in V(i)$, given that C_j transmits, is φ_0 for all $i = 1, 2, ..., K$ and all $C_j \in V(i)$. Our assumptions here are similar to those made in [1] in the context of packet radio networks.

Exact calculation of Th_j is difficult in that we need to consider the Markov chain whose state is comprised of the state (backlogged, B, or unbacklogged, UB) of every terminal using the uplink channel. Such a chain is difficult to analyze. Therefore, following [1] we employ an approximate method as follows. Let ϵ_i denote the probability of the event that B_i hears a node other than A_i. In general, ϵ_i depends on the current state of every node in the network. We use the approximation that ϵ_i depends only on the steady state distribution of the nodes in $H(i)$ and not on the actual states of any nodes in the network.

For $j = 1, 2, ..., K$, let X_n^j denote the state of A_j at the beginning of time slot n. Then our assumptions imply that $\{X_n^j\}$ is a Markov chain with state space $\{UB, B\}$ whose transition probabilities depend on ϵ_j. Furthermore, for $i \neq j$, $\{X_n^i\}$ and $\{X_n^j\}$ are statistically independent.

To evaluate the throughput of terminal A_i we first have to determine ϵ_i. We can write,

$$\epsilon_i = 1 - P_{0,i} \prod_{j \neq i : A_j \in U(i)} P_{j,i}, \quad \text{for} \;\; i = 1, 2, ..., K, \tag{1}$$

where for $j \neq 0$, $P_{j,i}$ is the probability that terminal $A_j \in U(i)$ is not heard at B_i in a given slot and where $P_{0,i}$ is the probability that B_i hears no transmission from the set $V(i)$. Now, in turn, $P_{j,i}$ depends on ϵ_j and is derived in the following.

Let $\boldsymbol{\pi}^j$=[ν_1^j, ν_2^j], where ν_1^j and ν_2^j are the steady state probabilities of unbacklogged and backlogged states of $\{X_n^j\}$, respectively. We have

$$\nu_1^j = \frac{q_r'(1 - \epsilon_j)}{q_r'(1 - \epsilon_j) + p_0 \epsilon_j} \quad \text{and} \quad \nu_2^j = \frac{p_0 \epsilon_j}{q_r'(1 - \epsilon_j) + p_0 \epsilon_j}. \tag{2}$$

Now $Pr(A_j$ transmits in a slot$)$=$\nu_1^j p_0 + \nu_2^j q_r'$. Therefore, $P_{j,i} = 1 - (\nu_1^j p_0 + \nu_2^j q_r')\varphi_{j,i}$.

We now evaluate $P_{0,i}$. Let $m_i = |V(i)|$ denote the number of nodes in the set $V(i)$. Given that n_i terminals out of m_i are backlogged, the probability, $P_{TX}(w)$, that w terminals transmit in a slot is given by

$$P_{TX}(w) = \sum_{b=0}^{w} \binom{n_i}{b} \binom{m_i - n_i}{w - b} (1 - q_r)^{n_i - b} (1 - p_0)^{m_i - n_i - w + b} p_0^{w-b} q_r^b, \tag{3}$$

and the probability that none of these w terminals is heard at B_i is given by $P_{TX}(w)(1 - \varphi_0)^w$. Summing over w, we get that the probability, $p_{0,i}(n_i)$, that no terminal of the set $V(i)$ is heard at B_i given that n_i of these are backlogged is given by

$$p_{0,i}(n_i) = \sum_{w=0}^{m_i} P_{TX}(w)(1 - \varphi_0)^w. \tag{4}$$

Then

$$P_{0,i} = \sum_{n_i=0}^{m_i} p_{0,i}(n_i) p(n_i|m_i), \tag{5}$$

where $p(n_i|m_i)$ is the probability that n_i terminals out of m_i are backlogged. It can be seen that

$$p(n_i|m_i) = \sum_{n=n_i}^{m-m_i+n_i} \frac{\binom{m_i}{n_i}\binom{m-m_i}{n-n_i}}{\binom{m}{n}} \pi_n, \tag{6}$$

where, as before, π_n is the steady state probability that n nodes in subnetwork 0 are backlogged.

In the above system of equations (1)-(6), we observe that if the $P_{0,i}$ and $P_{j,i}$, $i, j = 1, 2, ..., K$, are known, then the ϵ_i's can be calculated from (1). Conversely, if the ϵ_i's are known, then from (2)-(6) the $P_{0,i}$ and $P_{j,i}$, $i, j = 1, 2, ..., K$, can be calculated. This suggests that an effective computational procedure to calculate the K unknowns, $\epsilon_1, \epsilon_2, ..., \epsilon_K$, is iterated repeated substitution [14]. Once ϵ_j is determined the throughput of terminal A_j is given by

$$Th_j = [\nu_1^j p_0 + \nu_2^j q_r'](1 - \epsilon_j) \quad (1 \leq j \leq K). \tag{7}$$

3.2 Uplink Delay

Average packet delay is the average number of time slots from the time of acceptance of a new packet until its successful reception at its destination. Using Little's theorem, the average delay of the packets in subnetwork 0 is given by

$$D_0^{(u)} = 1 + \frac{\sum_{n=0}^{m} \pi_n n}{\sum_{n=0}^{m} \pi_n P_{succ}(n)} \tag{8}$$

where we have also accounted for the packet transmission time of one unit. Similarly, the average packet delay at terminal A_j is given by $D_j^{(u)} = 1 + \frac{\nu_2^j}{Th_j}$. Finally, the average delay for packets on the uplink channel is given by

$$D^{(u)} = \frac{\sum_{i=0}^{K} Th_i D_i^{(u)}}{\sum_{i=0}^{K} Th_i}. \tag{9}$$

4 Throughput and Delay on the Downlink Channel

The packets destined for the m terminals in subnetwork 0 arrive at the base station and are transmitted on the downlink channel. The arrival process is assumed to be a Bernoulli process with probability mp_0 that a packet arrives in a slot. Packet arrival for peer-to-peer terminals for the downlink channel is also assumed to be Bernoulli with probability p_0 that a packet arrives in a slot. All arrival processes are assumed to be independent. As stated previously, all terminals (including the base station) are assumed to have a buffer of size one.

Let $G(i)$ denote the set of nodes whose transmission on the downlink channel can be heard by A_i. Given that a node $B_j \in G(i) - \{B_i\}$ transmits in a given slot, we assume that the event that this transmission is heard by A_i is independent of all other previous and current events in the network and has a fixed (conditional) probability $\gamma_{j,i}$. The matrix $\Gamma = [\gamma_{i,j}]$ is referred to as the interference matrix on the downlink channel.

4.1 Downlink Throughput

BS period

Since the base station's transmissions are collision free, the average number of packets transmitted by the base station in the $T - s$ slots of the BS period is given by

$$N_{\text{BS}} = 1 - (1 - mp_0)^{(s+1)} + (T - s - 1)mp_0 \tag{10}$$

and the base station throughput is given by $Th^{(d)}_{\text{BS}} = \frac{N_{\text{BS}}}{T}$.

P-P period

During the P-P period, the probability that a node has a packet for transmission in the first slot is higher than in any other slot. Thus the probability that a node A_j hears a transmission from some node $B_i \in G(j) - \{B_j\}$, varies from one slot to another. Suppose that given that the current slot is α, the probability that A_j hears a transmission from some node $B_i \in G(j) - \{B_j\}$ in slot $\alpha + 1$ is given by $\delta_j^{(\alpha)}$, where $\alpha \in \{1, 2, ..., s\}$ and where here and in the following, superscripts referring to slots in the P-P period are all calculated mod s. Furthermore, as in the case of the uplink channel, we assume that for $\alpha = 1, 2, ..., s$ and $j = 1, 2, ..., K$, $\delta_j^{(\alpha)}$ depends only on the steady state distribution of the nodes in $G(j) - \{B_j\}$ and not on the actual states of any nodes in the network.

For $j = 1, 2, ..., K$, let (Y_n^j, s_n) denote the state of terminal B_j where $Y_n^j \in \{UB, B\}$ denotes the status (backlogged or unbacklogged) of the terminal and $s_n \in \{1, 2, ..., s\}$ is the current slot of the P-P period. With the above assumptions, $\{(Y_n^j, s_n)\}$ is a Markov chain whose transition probabilities can be determined from the $\delta_j^{(\alpha)}$'s. In particular,

$$
\begin{aligned}
Pr[(UB,\alpha),(B,\alpha+1)] &= p_0\delta_j^{(\alpha)} \qquad\qquad \alpha \neq 1 && (11)\\
Pr[(UB,1),(B,2)] &= [1-(1-p_0)^{(T-s+1)}]\delta_j^{(1)} && (12)\\
Pr[(B,\alpha),(UB,\alpha+1)] &= q'_r(1-\delta_j^{(\alpha)}). && (13)
\end{aligned}
$$

Given $\delta_j^{(\alpha)}$ for $j = 1,2,...,K$ and $\alpha = 1,2,...,s$, from the above equations we can evaluate the stationary distribution of $\{(Y_n^j, s_n)\}$ for $j = 1,2,...,K$. Conversely, given the stationary distributions, the $\delta_j^{(\alpha)}$'s can be evaluated as follows.

Let $Q_{i,j}^{(\alpha)}$ denote the (conditional) probability that in slot $\alpha+1$, node $B_i \in G(j)-\{B_j\}$ is not heard by node A_j given that the current slot is α. We then have $\delta_j^{(\alpha)} = 1-\prod_{i\neq j:B_i\in G(j)} Q_{i,j}^{(\alpha)}$. We now evaluate $Q_{i,j}^{(\alpha)}$. Let $\mu_{1,i}^{(\alpha)}$ and $\mu_{2,i}^{(\alpha)}$ be the steady state probabilities of finding node B_i in states (UB,α) and (B,α), respectively, i.e., $\mu_{1,i}^{(\alpha)} = Pr[(Y_n^i, s_n) = (UB,\alpha)]$ and $\mu_{2,i}^{(\alpha)} = Pr[(Y_n^i, s_n) = (B,\alpha)]$. Then since for $\alpha = 1,2,...,s$, $Pr(s_n = \alpha) = 1/s$, $Pr(Y_n^i = UB|s_n = \alpha) = s\mu_{1,i}^{(\alpha)}$. Similarly, $Pr(Y_n^i = B|s_n = \alpha) = s\mu_{2,i}^{(\alpha)}$. Therefore,

$$
Pr(B_i \text{ transmits in slot } \alpha+1|s_n=\alpha) = s\mu_{1,i}^{(\alpha)}q_a + s\mu_{2,i}^{(\alpha)}q'_r,
$$

where

$$
q_a = \begin{cases} p_0 & \alpha \neq 1 \\ 1-(1-p_0)^{(T-s+1)} & \alpha = 1. \end{cases} \qquad (14)
$$

Consequently,

$$
Q_{i,j}^{(\alpha)} = 1-(s\mu_{1,i}^{(\alpha)}q_a + s\mu_{2,i}^{(\alpha)}q'_r)\gamma_{i,j}. \qquad (15)
$$

Equations (11)-(15) are a set of nonlinear equations in $\mu_{i,j}^{(\alpha)}$ for $i = 1,2$, $j = 1,2,...,K$ and

$\alpha = 1, 2, ..., s$, that can be solved numerically using the iterated repeated substitution described earlier. This procedure also produces $\delta_j^{(\alpha)}$ for $j = 1, 2, ..., K$ and $\alpha = 1, 2, ..., s$.

The throughput of terminal B_i in slot $\alpha + 1$ is now given by

$$Th_i^{(d)}(\alpha + 1) = [s\mu_{1,i}^{(\alpha)} q_a + s\mu_{2,i}^{(\alpha)} q_r'](1 - \delta_i^{(\alpha)}), \tag{16}$$

and the throughput of terminal B_i on the downlink channel is given by $Th_i^{(d)} = \frac{1}{T}\sum_{\alpha=1}^{s} Th_i^{(d)}(\alpha)$. Finally, the throughput on the downlink channel is given by $S^{(d)} = Th_{\mathrm{BS}}^{(d)} + \sum_{i=1}^{K} Th_i^{(d)}$.

4.2 Downlink delay

Using Little's theorem does not simplify the delay calculation on the downlink channel because the calculation of the average number of packets in a subnetwork is difficult. We therefore apply a direct method.

Base Station

For a packet transmitted in slot $i \neq 1$ of the BS period, the average delay is equal to the transmission time of one slot. For the packets transmitted in the first slot of the BS period the average delay is $R + 1$ where R is the mean residual delay and is given by

$$R = \frac{s - (s+1)(1 - mp_0) + (1 - mp_0)^{s+1}}{mp_0 q_{a0}}, \tag{17}$$

where $q_{a0} = 1 - (1 - mp_0)^{s+1}$ is the probability that there is a packet to be transmitted in the first slot of the BS period. Therefore, the average delay of the packets transmitted by the base station is given by

$$D_{BS}^{(d)} = \frac{q_{a0}(R + 1) + (T - s - 1)mp_0}{q_{a0} + (T - s - 1)mp_0}. \tag{18}$$

Subnetwork i

Let $D_{i,\alpha}^{(d)}$ denote the average delay of the packets from node B_i which for the first time are transmitted in slot α. Then it can be shown [10] that

$$\begin{aligned} D_{i,\alpha}^{(d)} = \quad & \Upsilon + (1-\delta_i^{(\alpha-1)}) + \delta_i^{(\alpha-1)}\Big\{\frac{Tx}{(1-xy)^2}\big\{p_1 + (1-p_1)p_2 + ... \\ & +(1-p_1)(1-p_2)...(1-p_{s-1})p_s\big\} + \frac{x}{(1-xy)}\big\{2p_1 + 3(1-p_1)p_2 + \\ & +...... + (s+1)(1-p_1)(1-p_2)....(1-p_\alpha)(1-p_{\alpha+1})..(1-p_{s-1})p_s\big\} \\ & -\frac{\alpha x}{(1-xy)}\big\{p_1 + (1-p_1)p_2 + ... + (1-p_1)(1-p_2)..(1-p_{s-1})p_s\big\} \\ & +2p_{\alpha+1} + 3(1-p_{\alpha+1})p_{\alpha+2} + 4(1-p_{\alpha+1})(1-p_{\alpha+2})p_{\alpha+3} + ... \\ & \quad ...... + (s-\alpha+1)(1-p_{\alpha+1})(1-p_{\alpha+2})...(1-p_{s-1})p_s\Big\} \end{aligned} \tag{19}$$

where

$$\Upsilon = \begin{cases} \frac{(T-s)-(T-s+1)(1-p_0)+(1-p_0)^{T-s+1}}{p_0[1-(1-p_0)^{T-s+1}]} & \text{if } \alpha{=}1 \\ 0 & \text{otherwise,} \end{cases} \tag{20}$$

$$x = (1-p_{\alpha+1})(1-p_{\alpha+2})(1-p_{\alpha+3})....(1-p_s), \tag{21}$$

$$y = (1-p_1)(1-p_2)(1-p_3).....(1-p_\alpha), \tag{22}$$

and where p_α, the probability that a backlogged packet is transmitted successfully from B_i to A_i in slot α, is equal to $q_r'(1-\delta_i^{(\alpha-1)})$ for $\alpha = 1, 2, ..., s$.

Now let $D_i^{(d)}$ denote the average delay experienced by packets of terminal B_i. Then

$$D_i^{(d)} = \frac{\sum_{\alpha=1}^{s} \mu_{1,i}^{(\alpha)} q_a D_{i,\alpha}^{(d)}}{\sum_{\alpha=1}^{s} \mu_{1,i}^{(\alpha)} q_a}, \tag{23}$$

where q_a is given in (14).

Finally, the average delay experienced by packets of peer-to-peer terminals on the downlink channel is given by

$$D_{\text{P-P}}^{(d)} = \frac{\sum_{i=1}^{K} D_i^{(d)} Th_i^{(d)}}{\sum_{i=1}^{K} Th_i^{(d)}}, \tag{24}$$

and the average delay of the packets transmitted on the downlink channel is given by

$$D^{(d)} = \frac{D_{\text{BS}}^{(d)} Th_{\text{BS}}^{(d)} + D_{\text{P-P}}^{(d)} \sum_{i=1}^{K} Th_i^{(d)}}{Th_{\text{BS}}^{(d)} + \sum_{i=1}^{K} Th_i^{(d)}}. \tag{25}$$

5 Numerical Results

In this section we present numerical results for 2 networks and compare the results with those from simulation. On the uplink channel the interference matrix for network k, $k = 1, 2$, is given by Φ_k. We assume that if node A_i's transmission is heard at B_j, then node B_j's transmission is also heard at A_i and so the interference matrix on the downlink channel, Γ, is equal to Φ_k^T.

Network 1 consists of 12 nodes communicating with the BS and 6 peer-to-peer communicating pairs with $m_1 = 0, m_2 = 3, m_3 = 2, m_4 = 2, m_5 = 1$ and $m_6 = 1$. Network 2 also consists of 12 terminals communicating with the base station and 6 peer-to-peer communicating pairs with $m_1 = 4$, $m_2 = 3$, $m_3 = 4$, $m_4 = 4$, $m_5 = 4$, and $m_6 = 4$. The interference matrices are given by

$$\Phi_1 = \begin{bmatrix} 0 & \phi & 0 & 0 & 0 & 0 \\ \phi & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \phi & 0 & 0 \\ 0 & 0 & \phi & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \qquad \Phi_2 = \begin{bmatrix} 0 & \phi & \phi & 0 & \phi & 0 \\ \phi & 0 & \phi & 0 & 0 & 0 \\ \phi & \phi & 0 & 0 & \phi & 0 \\ \phi & \phi & \phi & 0 & \phi & \phi \\ \phi & 0 & \phi & \phi & 0 & \phi \\ 0 & 0 & 0 & \phi & \phi & 0 \end{bmatrix},$$

where ϕ is a constant. We consider two cases of $\phi = 0.1$ and $\phi = 1$. For $\phi = 0.1$ the interference is quite limited but for $\phi = 1$ every interferer's transmission is heard with probability one. (As can be seen from the interference matrices, network 1 represents the case of small peer-to-peer interference and network 2 represents the case of large peer-to-peer interference.) Also, for the uplink channel we consider two cases of $\phi_0 = .5$ and $\phi_0 = 1$. For network 1 we chose $q_r = .25$ and $q_r' = .5$ and for network 2 we chose $q_r = .25$ and $q_r' = .4$. These values were found to result in good throughput and delay performance.

In all the figures we have plotted the throughput or delay versus the total arrival rate on the uplink channel or the downlink channel (which is $18p_0$ for the entire network and $6p_0$ for all the peer-to-peer subnetworks). Figures 2, 3, 4 and 5 show the total throughput on the uplink channel for networks 1 and 2 with $\phi = 0.1$ and 1. From these figures it can be seen that, due to peer-to-peer communication, the throughput can be significantly higher than that of slotted Aloha without peer-to-peer communication which has a maximum throughput of .368 [4]. For network 1 where the number of interferers for peer-to-peer terminals is small, the throughput is nearly independent of the value of ϕ. For network 2 in the case of $\phi = .1$, the interference for the peer-to-peer terminals is low and the throughput is close to that of network 1. However, as ϕ increases to 1, there is a significant reduction in network throughput. Furthermore, for the case of small interference (network 1 and network 2 with $\phi = .1$), the throughput does not reach a maximum for the range of arrival rates considered. Clearly $\phi_0 = .5$ results in a higher throughput than $\phi_0 = 1$ since the interference from subnetwork 0 is smaller and this effect is more significant as the arrival rate increases. These figures also show a close agreement between the calculation and the simulation results validating the modeling assumptions in our analysis.

Figures 6, 7, 8 and 9 show the average delay on the uplink channel for the terminals in subnetwork 0 and for peer-to-peer terminals. These plots show that, as expected, the peer-to-peer terminals experience significantly smaller delay on the uplink channel than the terminals in subnetwork 0. We note that the average delay reaches a constant as the arrival rate increases. This is of course due to the fact that each node has a buffer of size one and arriving packets to backlogged nodes are discarded.

For the downlink channel we have selected a frame length of $T = 20$ slots and have examined the cases of $s = 2$, 3 and 4. Figures 10, 11, 12 and 13 show the total throughput of peer-to-peer subnetworks on the downlink channel for networks 1 and 2 for different values of s. As in the case of the uplink channel, for network 1 the throughput is close for $\phi = .1$ and $\phi = 1$ and is very close to that of network 2 with $\phi = .1$. However, for the case of network 2 with $\phi = 1$ (very large interference for peer-to-peer terminals), the throughput reaches its maximum at small values of the arrival rate. Clearly, as the number of slots reserved for peer-to-peer subnetworks increases, the throughput increases. The throughput for subnetwork 0 is the same for the two networks and is independent of ϕ. It was found that the total network throughput does not vary significantly with s. Rather, the choice of s determines how the total throughput is divided between subnetwork 0 and the peer-to-peer subnetworks.

Figures 14, 15, 16 and 17 show the average delay on the downlink channel for peer-to-peer subnetworks. This average delay has two components both of which decrease as s increases. First, packets which arrive in the last slot of the P-P period or during the BS period have to wait for the next P-P period to be transmitted. This is the residual delay which decreases as s increases. Next, is the delay of packets which are transmitted in slot α, $2 \leq \alpha \leq s$, which also reduces with s. Finally the average delay of the BS on the downlink channel is the same for the two networks and is independent of ϕ. This delay increases with s as the delay for the packets that are transmitted in slot 1 of the BS period increases with s.

6 Conclusions

We have presented a MAC protocol for a packet switched wireless LAN which supports peer-to-peer communication. Throughput and delay of the protocol is analyzed. Numerical results from analysis are presented along with simulation results. The results show that a significant improvement in delay/throughput can be achieved over a MAC protocol using slotted Aloha without peer-to-peer communication.

References

[1] A. Bar-David, and Moshe Sidi, "Collision Resolution Algorithms in Multistation Packet-Radio Networks," *IEEE Transactions on Communications*, vol. 37, no. 12, pp. 1387-1391, December 1989.

[2] Christian Namislo, "Analysis of Mobile Radio Slotted ALOHA Networks," *IEEE Journal on Selected Areas in Communications*, vol. SAC-2, no. 4, pp. 583-588, July 1984.

[3] Chung-Chin Lu, and Chi-Yung Ko, "A Media Access Control Protocol Architecture For Wireless Local Area Networks," *IEEE International Conference on Communications*, pp. 1005-1009, May 1993.

[4] Dimitri Bertsekas and Robert Gallager, *Data Networks.* 2nd ed., Englewood Cliffs, NJ, Prentice-Hall, 1992.

[5] Gang Wu, Kaji Mukumoto, and Akira Fukuda, "Slotted Idle Signal Multiple Access with Collision Detection for Two-Way Centralized Wireless Communication Networks," *IEEE International Conference on Communications*, pp. 995- 999, May 1993.

[6] Katsumi Sakakibara, "Performance Approximation of a Multi-Base Station Slotted ALOHA for Wireless LAN's," *IEEE Transactions on Vehicular Technology*, vol. 41, no. 4, pp. 448-454, November 1992.

[7] K.C.Chua, "A Variant of the CSMA Protocol Suitable for a Mobile Radio LAN," *IEEE GLOBECOM*, pp. 1354-1358, December 1992.

[8] K.C. Chua, "Performance Modeling of an Idle-Signal Casting Multiple Access with Failure Detection (ICMA/FD) Mobile PRLAN," *IEEE Conference on Communications*, pp. 1017-1021, May 1993.

[9] Richard O. LaMaire, Arvind Krishna, and Pravin Bhagwat, "Wireless LAN's and mobile networking: standards and future directions," *IEEE Communications Magazine*, pp. 86-94, August 1996.

[10] M. Naraghi-Pour and M. Hegde, "Peer-to-peer communication in wireless networks," LSU Technical report, 1997.

[11] L. Goldberg, "Wireless LANs: Mobile Computing's Second Wave," *Elect. Design,* vol. 43, June 26, 1995, 55-72.

[12] C. Links, W. Diepstraten and V. Hayes, "Universal Wireless LANs," Byte, vol. 19, May 1994, pp. 99-108.

[13] H. Ahmadi, A. Krishna and R. O. LaMaire, "Design issues in Wireless LANs," *J. High-Speed Networks*, vol. 5, no. 1, 1996, pp. 87-104.

[14] Dimitri Bertsekas and Johhn Tsitsiklis, *Parralel and Distributed Computation, Numerical methods*, Englewood Cliffs, NJ, Prentice-Hall, 1989.

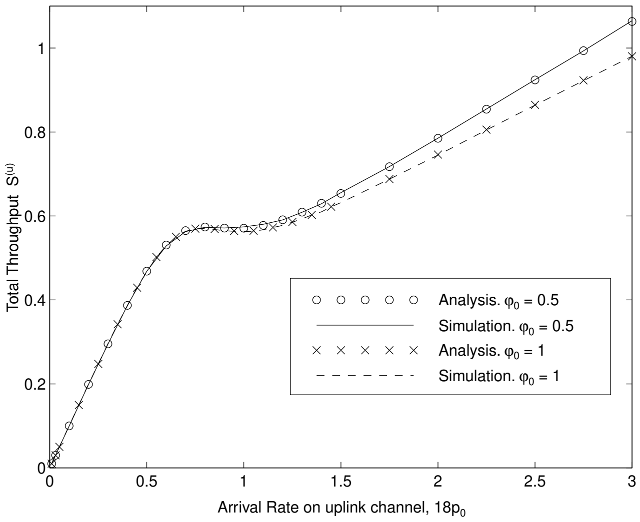

Figure 2: Throughput on the uplink channel for network 1, $\phi = 0.1$.

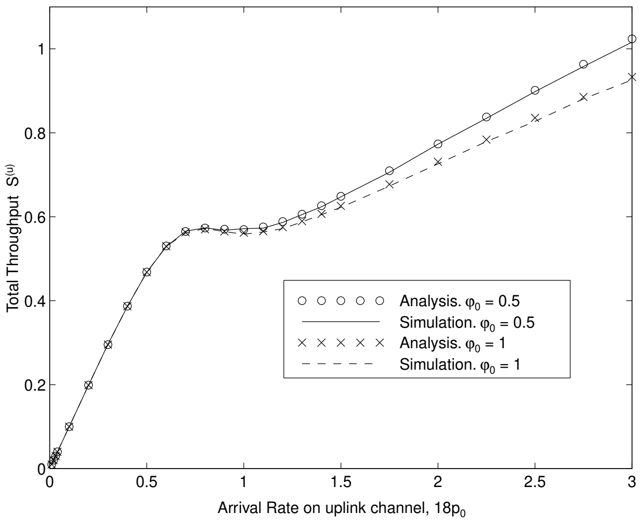

Figure 3: Throughput on the uplink channel for network 1, $\phi = 1$.

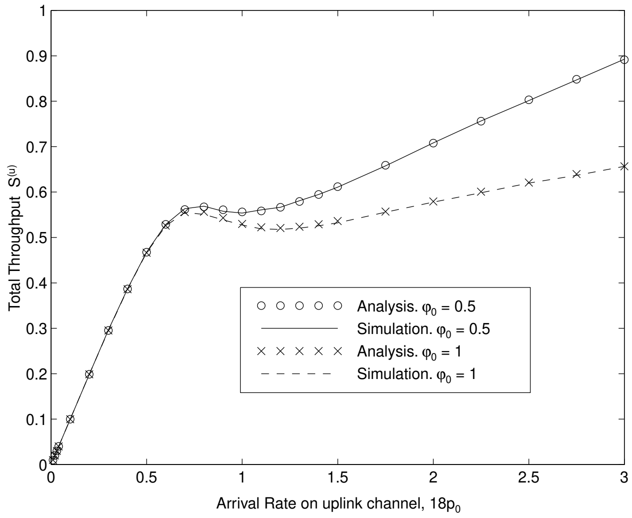

Figure 4: Throughput on the uplink channel for network 2, $\phi = 0.1$.

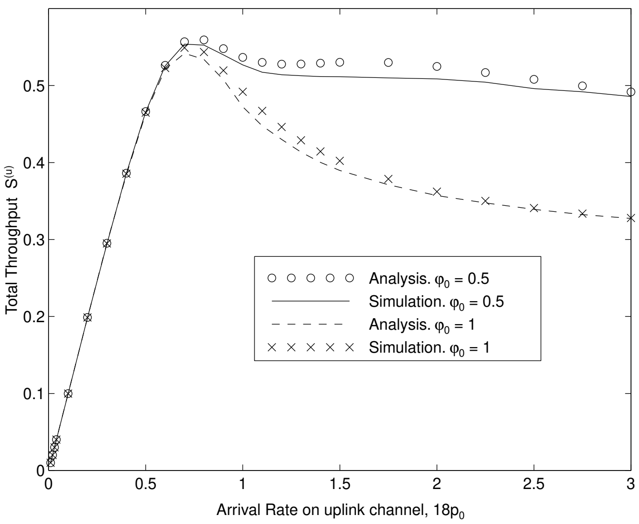

Figure 5: Throughput on the uplink channel for network 2, $\phi = 1$.

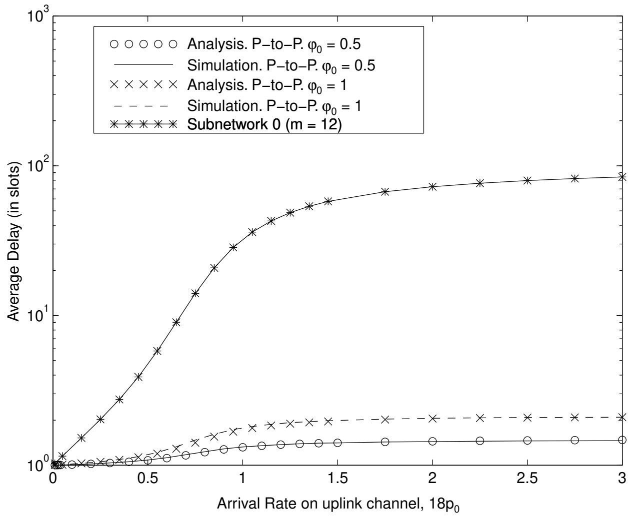

Figure 6: Average Delay $D^{(u)}$ for network 1, $\phi = 0.1$.

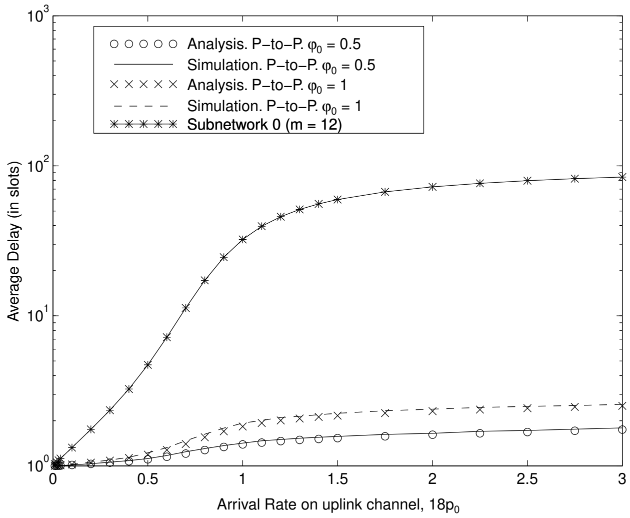

Figure 7: Average Delay $D^{(u)}$ for network 1, $\phi = 1$.

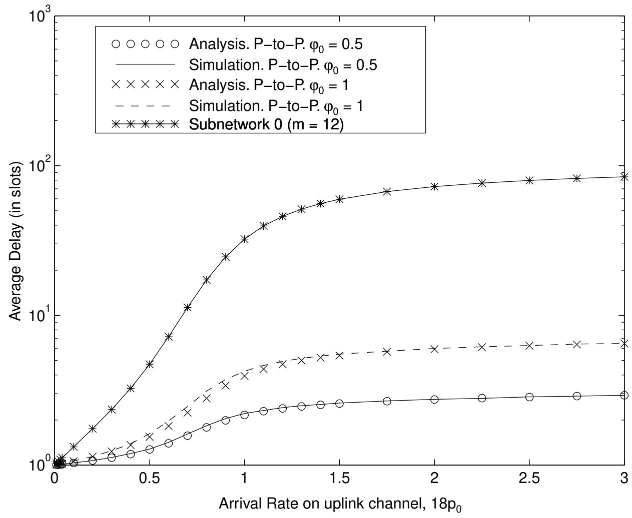

Figure 8: Average Delay $D^{(u)}$ for network 2, $\phi = 0.1$.

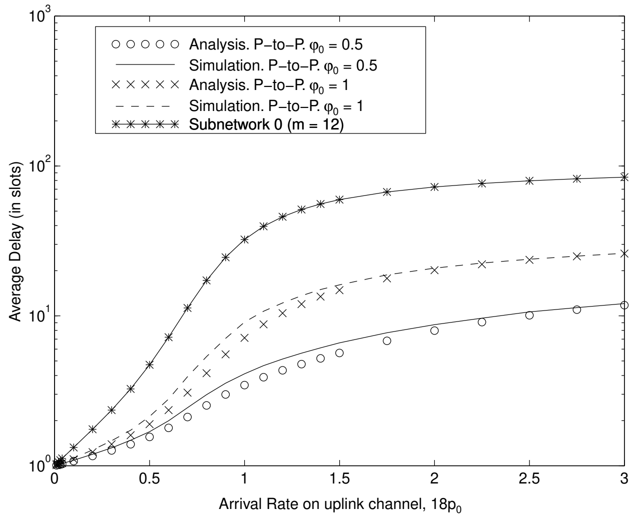

Figure 9: Average Delay $D^{(u)}$ for network 2, $\phi = 1$.

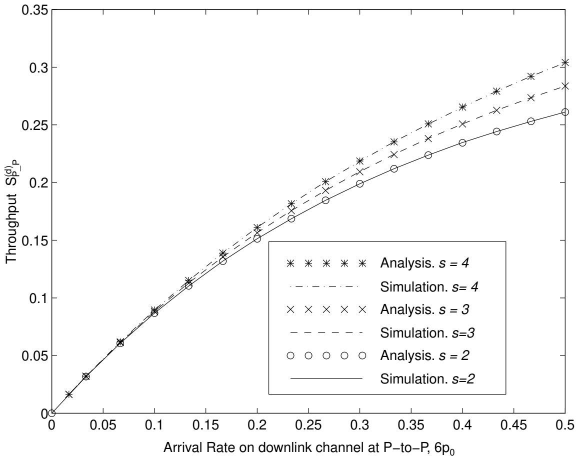

Figure 10: Throughput on the downlink channel for peer-to-peer subnetworks of network 1, $\phi = 0.1$.

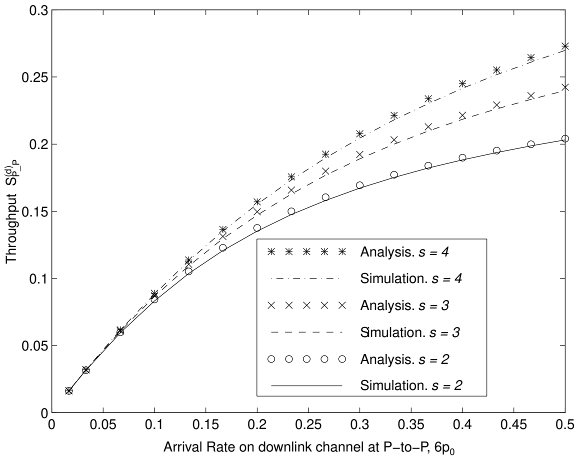

Figure 11: Throughput on the downlink channel for peer-to-peer subnetworks of network 1, $\phi = 1$.

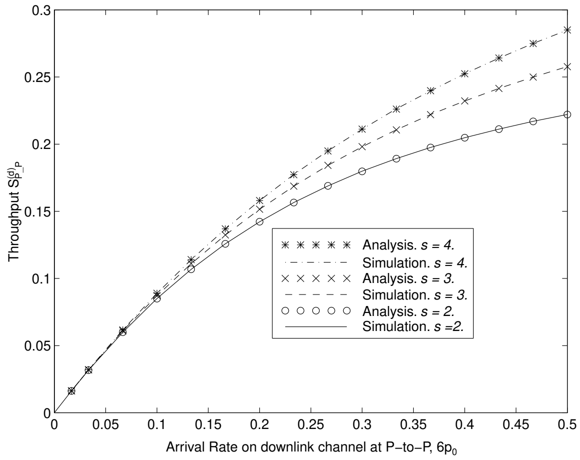

Figure 12: Throughput on the downlink channel for peer-to-peer subnetworks of network 2, $\phi = 0.1$.

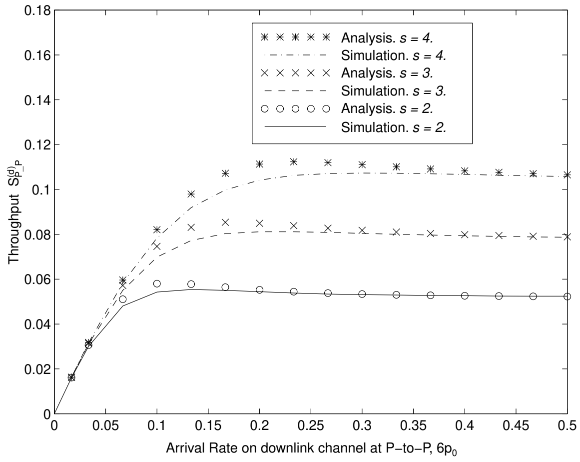

Figure 13: Throughput on the downlink channel for peer-to-peer subnetworks of network 2, $\phi = 1$.

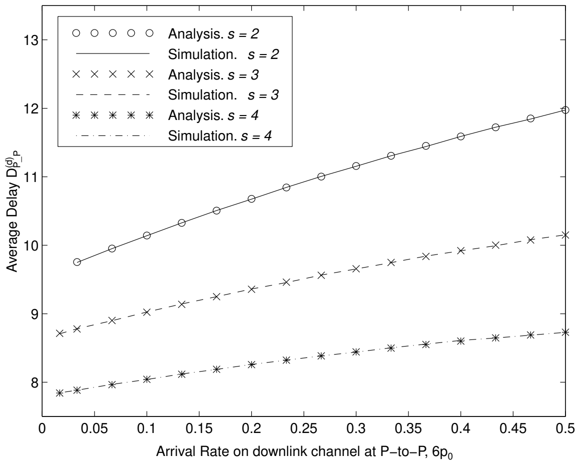

Figure 14: Average Delay on the downlink channel for peer-to-peer subnetworks of network 1 with $\phi = 0.1$.

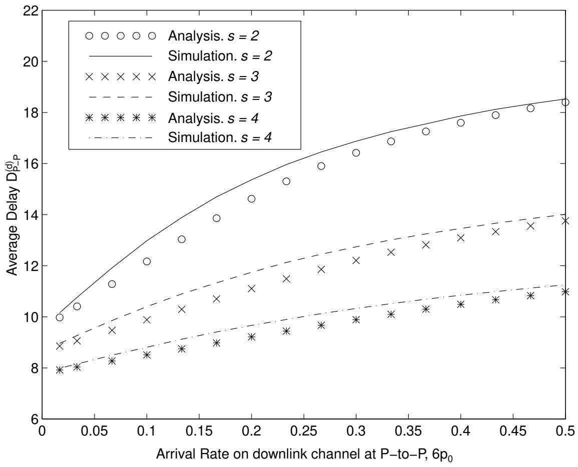

Figure 15: Average Delay on the downlink channel for peer-to-peer subnetworks of network 1, $\phi = 1$.

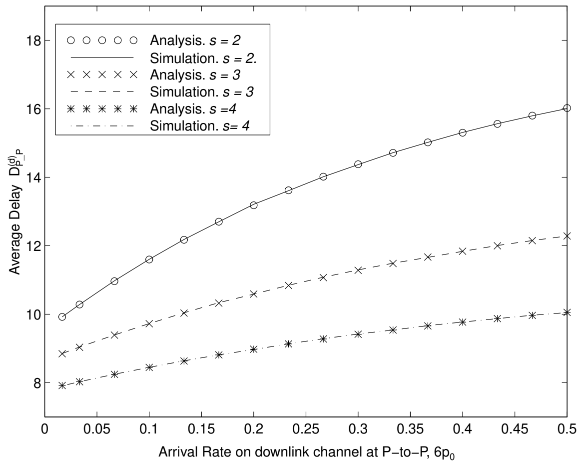

Figure 16: Average Delay on the downlink channel for peer-to-peer subnetworks of network 2, $\phi = 0.1$.

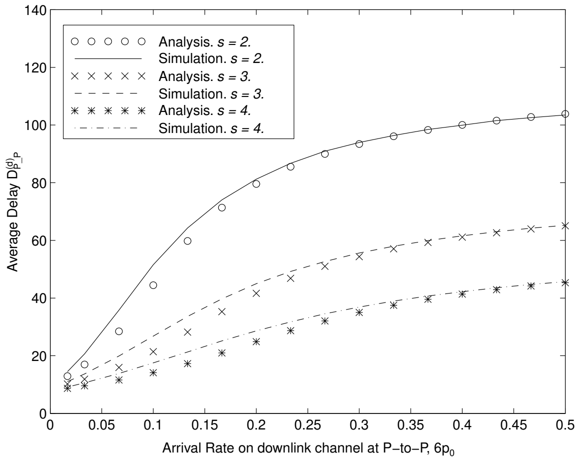

Figure 17: Average Delay on the downlink channel for peer-to-peer subnetworks of network 2, $\phi = 1$.