Performance Analysis of the Out-of-Band Signaling Scheme for High Speed Wireless LANs

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***Abstract*— In this paper, we study the performance of our earlier proposed Out-of-Band Signaling (OBS) scheme for high speed wireless local area networks (WLANs). We employ the system approximation technique for the modeling of the OBS scheme. An equivalent state dependent single server queue that describes the OBS scheme is constructed for the analysis of the throughput and delay performances. Moreover, we study the throughput optimization of the OBS scheme, which provides a mean for optimizing the performance of the OBS scheme given a particular network environment. Finally, we conduct several simulation experiments to validate our analytical results.**

I. Introduction

The emergence of high speed wireless local area networks (WLANs), such as the IEEE 802.11a and IEEE 802.11g, has provided a high speed networking solution for mobile users to access a network in addition to the popular IEEE 802.11b solution. The IEEE 802.11a and 802.11g provide data rates up to 54 Mbps while the IEEE 802.11b provides data rates up to 11 Mbps.

The IEEE 802.11 [1] specifies two mechanisms for transmission which are the distributed coordination function (DCF) and the point coordination function (PCF). DCF makes use of CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) with binary exponential backoff for contention and resolving transmission collision. PCF is an optional contention-free service which makes use of polling by the centralized point coordinator (PC). Furthermore, DCF employs two techniques for frame transmission. The default is a two-way handshaking method called basic access method. Another technique employs a four-way handshaking method, known as Request-To-Send/Clear-To-Send (RTS/CTS).

With the introduction of the high speed wireless date channel in IEEE 802.11a and IEEE 802.11g, some recent studies ([2], [3]) have shown that the performance of the IEEE 802.11 MAC protocol drops as the channel data rate grows, and the throughput upper limit does exist when the channel data rate goes to infinite high. These findings indicate that the performance of a WLAN will not be efficiently improved by merely increasing the channel data rate.

In [4], we have introduced an out-of-band signaling (OBS) technique to improve the performance of a high speed WLAN with the use of a separate low speed channel for signaling. Our study indicates that the current in-band signaling method used in IEEE 802.11 on a high speed channel actually causes higher bandwidth wastage compared to our proposed out-of-band signaling method. The bandwidth gained from the use of two channels in OBS exceeds the bandwidth used for the signaling channel; hence, the overall system performance is improved. The performance advantages were demonstrated through several simulation studies in [4].

In this paper, we provide analytical studies of our earlier proposed OBS scheme. We compare the throughput and delay performances of the OBS scheme with that of the IEEE 802.11 schemes. We further study the throughput optimization of the OBS scheme, that is the data rate partition of a channel into signaling and data channels to achieve optimal system throughput. This study also provides a mean to obtain optimum network design should the OBS scheme be chosen for implementation.

This paper is organized as follow. Section II provides a brief summary of the IEEE 802.11 MAC protocol and the OBS scheme. Section III provides the analytical and simulation results of the OBS scheme. Section IV provides a method to optimize the data rate of signaling and data channels.

II. MAC Protocols

This section briefly summarizes the IEEE 802.11 and OBS MAC protocol. For detailed description, readers may refer to [1] and [4].

A. Distributed Coordination Function

The DCF employs CSMA/CA MAC protocol with binary exponential backoff. The DCF does not use collision detection function as the stations cannot detect collision by listening their own transmission; thus, it employs handshaking method, which makes use of positive acknowledgment.

The basic access mechanism employs a two-way handshaking method. When a station has a new frame to transmit, it will monitor the channel activity. If the channel is detected idle for a period of time called distributed interframe space (DIFS), the station can transmit immediately. If the channel is busy, the station will defer until the end of transmission and a random backoff interval is selected. The backoff counter is

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decremented as long as the channel is sensed idle, stopped when channel activity is detected, and reactivated when the channel is sensed idle for more than a DIFS again. The station transmits its frame when the backoff counter reaches zero.

The DCF uses a slotted binary exponential backoff technique. The period following an idle DIFS is slotted and the backoff time counter is measured in terms of slot time. The slot time is the time needed for any stations to detect transmission from any other stations. It accounts for the propagation delay, the time needed to switch from the receiving to the transmitting state and the time to notify the MAC layer about the state of the channel.

The backoff time is uniformly chosen in the range (0,CW-1), where CW is the current contention window. At the first transmission attempt, CW is set equal to the minimum contention window (CW_{min}). After each unsuccessful transmission, CW is doubled until it reaches the maximum contention window (CW_{max}).

When the destination station successfully receives a frame, it will transmit an acknowledgment frame (ACK) after a short interframe space (SIFS). If the sender does not receive the ACK within a specified ACK timeout, or it detects the transmission of a different frame on the channel, it reschedules the frame transmission according to the previous backoff rules.

The DCF also defines an optional four-way handshaking method for frame transmission, which is known as RTS/CTS method. When a station is ready for a transmission, it performs the previous backoff technique. The sender transmits a special RTS frame. When the receiver receives the RTS frame, it responds with CTS frame after a SIFS. The sender may then transmit the frame only if the CTS frame is correctly received.

The RTS and CTS frames carry the information of the length of the frame to be transmitted, which is used to update a network allocation vector (NAV) by other stations. The NAV contains the information about the period of time in which the channel will remain busy hence a station can delay transmission by detecting either RTS or CTS to avoid collision. The RTS/CTS method improves the system performance, especially when large frames are transmitted, as it reduces the length of the frames involved in the contention process.

B. Point Coordination Function

The IEEE 802.11 also specifies the optional PCF which is implemented on top of the DCF. The PCF operation makes use of polling by the PC; hence, it is contention free. The PC uses point coordination interframe space (PIFS) when issuing polls. The PIFS is longer than SIFS but shorter than DIFS, hence the PC can take control of the channel and stop all the asynchronous traffic while it issues polls and receives responses. In PCF, the ACK can be combined with data or poll frame, thus it has less overhead compared to DCF.

C. Out-of-Band Signaling Scheme

The OBS scheme can be briefly described as follows. OBS uses an unused channel operating at a lower speed for the channel assignment purposes. The actual data transmissions will be scheduled on the high speed channel. When a station is ready for a data transmission, it executes the DCF on the low speed channel to schedule its RTS control frame transmission. When the PC receives the RTS frame, the PC schedules the data transmission to the next PCF period on the high speed channel and acknowledges the request (see Fig. 1).

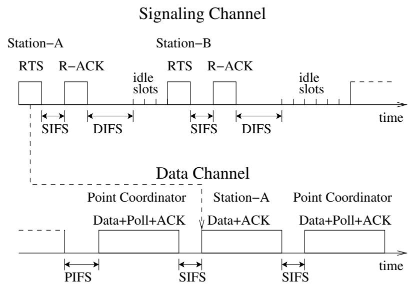

Fig. 1. The OBS scheme.

This mechanism improves the performance of WLANs as the costly idle periods and transmission collisions are avoided entirely on the high speed channel. As PCF imposes less overhead compared to the DCF (as ACK and poll can be combined with data), this mechanism has less overhead on data transmission. Therefore higher utilization can be achieved on the high speed channel.

III. Performance Evaluation

A. Analytical Study of Out-of-Band Signaling Scheme

We first define a *ready station* to be a station that is currently scheduling its RTS transmission on the signaling channel, a *backlogged station* to be a station that has exchanged its RTS/CTS message and currently waiting for a poll message from the PC on the data channel, and an *idle station* to be a station that has no frame for transmissions. An idle station switches to a ready station when it generates a frame into its local buffer. A ready station switches to a backlogged station when it has successfully exchanges the RTS/CTS message with the PC. After a successful frame transmission, a backlogged station switches to either an idle station if there is no more frame to transmit, or a ready station if there is at least one frame awaiting in its local buffer for transmissions. In this analysis, we consider a finite number of stations under saturation load condition [2]. With this load condition, a station will never become an idle station, a station simply alternates itself between a ready station and a backlogged station.

Applying the Markovian Framework modeling technique presented in [5], we model the OBS scheme into a single server queue (SSQ). Stations implementing the OBS scheme exchange RTS/CTS messages with the PC on the signaling channel, and the actual frame transmission is performed on the data channel using the PCF, which may not follow the RTS/CTS message exchange immediately (see Fig. 1). To describe such a system, we model the arrival process of the SSQ into the process that stations switch from ready stations to backlogged stations, and the service process of the SSQ into the process that stations switch from backlogged stations to ready stations. Hence, the state of the SSQ describes the number of backlogged stations in a network.

It is indicated in [5] that the service time distribution of the IEEE 802.11 MAC protocol under saturation load condition behaves like an Erlang distribution when a constant frame size is considered. In [5], the protocol service time consists of the time period for a successful RTS/CTS message exchange followed by a frame transmission, and these two time periods are independent. Since the frame transmission time is constant, the time period for a successful RTS/CTS message exchange also has an Erlang distribution, only with a different parameter.

In our SSQ model, the interarrival time of arrivals is the time period for a successful RTS/CTS message exchange, which has an Erlang distribution according to [5]. We further assume that the frame size is constant; we use an Erlang distribution to approximate this constant service time. With this construction, we build a state dependent E$_j$/E$_k$/1/n (SD-E$_j$/E$_k$/1/n) queue to model the OBS scheme. The arrival rate of our SSQ is state dependent because different number of ready stations requires different time duration to obtain a successful RTS/CTS message exchange on the signaling channel. The detailed state transition diagram of the SD-E$_j$/E$_k$/1/n with $j = 4$ and $k = 3$ is sketched in Fig. 2, and the balance equations set is provided by (1). The state $\{x,y,z\}$ in Fig. 2 represents the state that there are x backlogged stations in the network, a new arrival has reached its y-th Erlang phase out of j total phases, and the server has completed z-th Erlang phases out of k total phases of a frame transmission.

$$
\begin{aligned}
0 &= -j\lambda_0 P_{0,0,0} + k\mu P_{1,0,k-1} \\
0 &= -j\lambda_0 P_{0,y,0} + j\lambda_0 P_{0,y-1,0} + k\mu P_{1,y,k-1}, \\
&\quad 0 < y < j-1 \\
0 &= -(j\lambda_x + k\mu) P_{x,y,z} + j\lambda_x P_{x,y-1,z} + k\mu P_{x,y,z-1}, \\
&\quad 0 < x < n,\ 0 < y < j-1, 0 < z < k-1 \\
0 &= -(j\lambda_x + k\mu) P_{x,0,z} + j\lambda_{x-1} P_{x-1,j-1,z} + k\mu P_{x,0,z-1}, \\
&\quad 0 < x < n,\ 0 < z < k-1 \\
0 &= -(j\lambda_x + k\mu) P_{x,y,0} + j\lambda_x P_{x,y-1,0} + k\mu P_{x+1,y,k-1}, \\
&\quad 0 < x < n,\ 0 < y < j-1 \\
0 &= -(j\lambda_x + k\mu) P_{x,0,0} + j\lambda_{x-1} P_{x-1,j-1,0} + k\mu P_{x+1,0,k-1}, \\
&\quad 0 < x < n \\
0 &= -k\mu P_{n,0,z} + j\lambda_{n-1} P_{n-1,j-1,z} + k\mu P_{n,0,z-1}, \\
&\quad 0 < z < k-1 \\
0 &= -k\mu P_{n,0,0} + j\lambda_{n-1} P_{n-1,j-1,0}. \qquad (1)
\end{aligned}
$$

Assume that the total number of stations in a network is n. Let m be the number of backlogged stations, then the number of ready stations is $n - m$. The arrival rate λ_u is the rate of a successful RTS/CTS message exchange when there are $u = n - m$ ready stations, and the service rate μ is the rate of a frame transmission. Given in [4] and [2], λ_i is the IEEE 802.11 MAC protocol service rate using four-way handshake method excluding the frame transmission period, which is

$$\lambda_u = \frac{P_s P_{tr}}{(1 - P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1 - P_s) T_c}, \qquad (2)$$

where σ is the slot time, P_{tr} is the probability that in a slot time there is at least one transmission given u ready stations, and P_s is the probability that a transmission is successful. The values of T_s and T_c, the average time that the channel is sensed busy because of a successful transmission and the average time that the channel is sensed busy during a collision respectively, are given by

$$\begin{cases} T_s = RTS + SIFS + \delta + R\_ACK + DIFS + \delta \\ T_c = RTS + DIFS + \delta \end{cases}. \qquad (3)$$

The service rate of the SSQ, μ, is given by [4]

$$\mu = 1/T_{cycle}, \qquad (4)$$

where the T_{cycle} can be expressed as

$$T_{cycle} = T_{POLL} + SIFS + \delta + T_{DATA} + SIFS + \delta. \qquad (5)$$

With these parameters, we compute the numerical results of the SD-E$_j$/E$_k$/1/n queue with $j = k = 32$ [5] using Successive Over-Relaxation [6].

Let p_i be the probability that the there are i backlogged stations in the network, $0 \le i \le n$. Relating to the SSQ, $p_i = \sum_{y,z} \pi_{i,y,z}$, where $\pi_{x,y,z}$ is the steady state probability of the SSQ being in state $\{x, y, z\}$. The mean arrival rate of the SSQ, $\overline{\lambda}$, can be computed by

$$\overline{\lambda} = \sum_{i=0}^{n} (\lambda_{n-i} \cdot p_i), \qquad (6)$$

and the system throughput, γ, can be obtained by

$$\gamma = \overline{\lambda} \cdot d_t, \qquad (7)$$

where d_t is the mean transmission time of the payload in a frame.

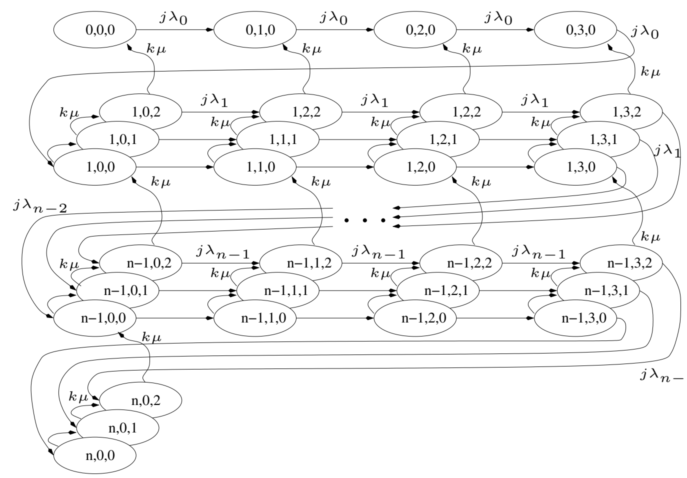

Fig. 2. Markov chain model of a E$_4$/E$_3$/1/n queue.

Let $\overline{m}$ be the average number of backlogged stations. The value $\overline{m}$ can be computed by

$$\overline{m} = \sum_{i=0}^{n}(i \cdot p_i). \tag{8}$$

Using Little's formula, we calculate the average queuing delay of a frame on the data channel, W, as

$$W = \overline{m}/\overline{\lambda}. \tag{9}$$

The average queuing delay corresponds to the time period between a successful RTS/CTS message exchange and the frame transmission time. This queuing delay time does not include the time period of the contention and RTS/CTS message transmission on the signaling channel. To include that, we simply need

$$W_s = n/\overline{\lambda}. \tag{10}$$

The above result is derived based on the concept that in the saturation condition, there are always n active stations in the network either competing on the signaling channel or waiting for frame transmission on the data channel. An arrival of the network is the generation of a new frame from any of the n stations, which occurs when a backlogged station switches to a ready station. Moreover, the rate for a backlogged station switching to a ready station is the same as the rate for a ready station switching to a backlogged station in steady state under saturation condition, where the latter is simply $\overline{\lambda}$ according to our SSQ model. Applying Little's formula, we obtain the mean transmission delay, W_s, of the protocol implementing the OBS scheme.

Fig. 3 shows the saturation throughput of the OBS scheme. The average transmission delay, W_s, of the OBS scheme is plotted in Fig. 4. Fig. 5 presents the average queuing delay of the OBS scheme. The symbols shown in the figures represents the simulation results, while the solid lines show the analytical results. The choice of 6 $Mbps$ for the signaling channel is based on the study presented in Section IV. The figures show close match between the analytical and the simulation results. These results are further confirmed by the results presented in [4], indicating the accuracy of our analysis. The result discussions are not the primary focus of this subsection, details of the study can be found in [4].

B. Performance Comparison

In this subsection, we present the delay results of the OBS scheme compared with the IEEE 802.11 schemes. The average transmission delay of IEEE 802.11 is derived using the the saturation throughput [2] with Little's formula similar to technique used for deriving (10). Fig. 6 shows the average transmission delay of the schemes in saturation condition. The transmission delay here corresponds to the time between the frame generation time to the end of the frame transmission. As we assume saturation condition, the end of a frame transmission is the generation time of a new frame.

In general, the OBS scheme provides lower delay than that of the IEEE 802.11 schemes as the contention and the frame transmission is separated. Using the OBS scheme, frame transmission does not delay the other stations from requesting a transmission to the PC; hence, it reduces the overheads of contention significantly. With small payload size, the basic access method can provide lower average delay compared with the RTS/CTS method.

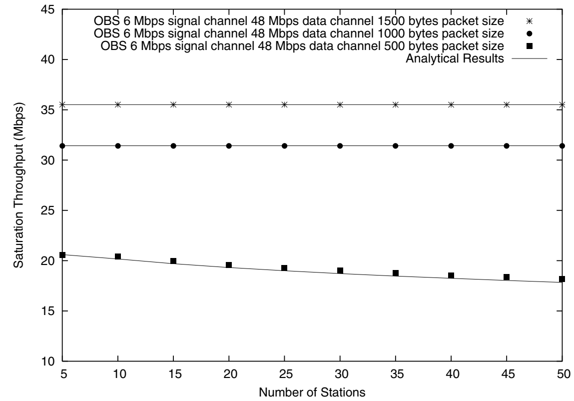

Fig. 3. Saturation throughput of OBS scheme.

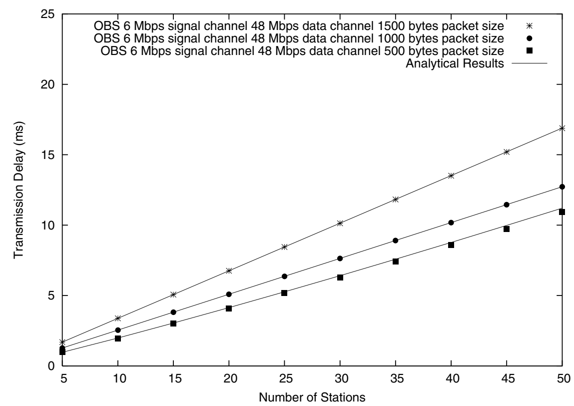

Fig. 4. Average transmission delay of OBS scheme.

IV. Throughput Optimization

This section provides an analytical study of throughput optimization of the OBS scheme. Precisely, given a wireless channel bandwidth measured in bps of a WLAN, what is the proportion of the bandwidth should the signaling channel receives to achieve an optimal system performance? Intuitively, a low data rate on the signaling channel will cause lengthy RTS/CTS message exchange, hence under utilizing the data channel. However, a high data rate on the signaling channel will cause more wastage as in the existing IEEE 802.11 MAC protocol, moreover less bandwidth will be assigned to the data channel which is used to carry actual frame transmissions. Therefore, it exists an optimal operation point for the OBS scheme with an appropriate choice of data rates for the signaling and the data channels.

To maximize the data channel utilization, we need $\frac{\lambda}{\mu} = 1$, that is when the rate of a successful RTS/CTS message exchange equals the frame transmission rate, which keeps the

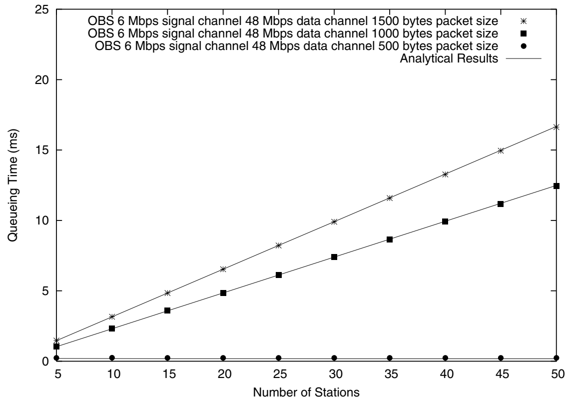

Fig. 5. Average queuing delay of OBS scheme.

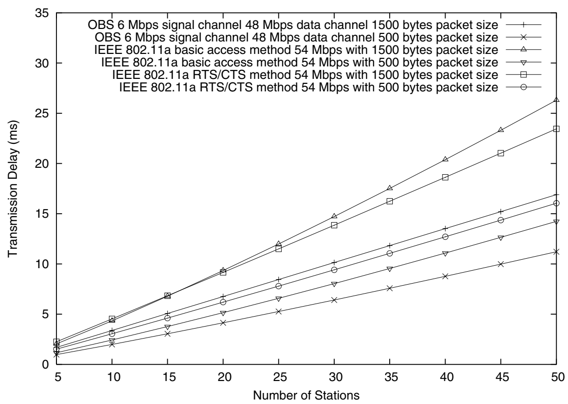

Fig. 6. Average transmission delay of OBS scheme compared with the IEEE 802.11a.

data channel fully utilized. The variable λ depends on the data rate of the signaling channel and the number of stations contending on the signaling channel, whereby the variable μ depends on the data rate of the data channel and the frame size. The first constraint function is $D = D_{sig} + D_{data}$, where D is the total bandwidth of a WLAN measured in bps, and D_{sig} and D_{data} are the data rates of the signaling channel and the data channel respectively.

We further define two functions: $\overline{\lambda}(D_{sig})$ and $\mu(D_{data})$. The function $\overline{\lambda}(D_{sig})$ describes the average rate of a successful RTS/CTS message exchange on the signaling channel given by (6), and the function $\mu(D_{data})$ describes the rate of a frame transmission on the data channel given by (5). Given a frame size and a particular number of stations in a WLAN, we use the following conditions to compute the data rate required for the signaling channel to fully utilize the data channel.

$$\begin{cases} D = D_{sig} + D_{data} \\ \frac{\overline{\lambda}(D_{sig})}{\mu(D_{data})} = 1 \end{cases} . \tag{11}$$

Using the above results, in Fig. 7 we show the signaling channel data rate requirement to achieve a fully utilized data channel for a range of total bandwidth. For medium and large frame sizes, OBS requires low data rate signaling channel to utilize high data rate data channel. For example, 10 Mbps signaling channel is enough to utilize a 98 Mbps data channel considering a 108 Mbps WLAN. With small frame sizes, OBS requires a higher data rate signaling channel to achieve full utilization on the data channel. For the case of 500 byte frames, the signaling channel data rate requirement remains under 10 Mbps to optimize system performance when the total bandwidth is under 54 Mbps. With this consideration, allocating a signaling channel operating at 6 Mbps seems to be a good choice for improving the performance of an existing 54 Mbps WLAN.

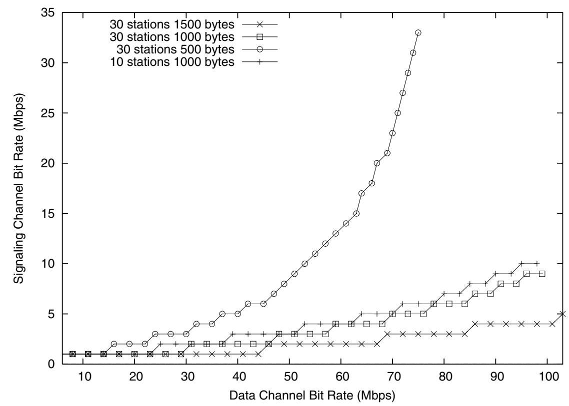

Fig. 7. Minimum signaling channel data rate required to achieve full utilization on the data channel for a total data rate up to 108 Mbps.

V. CONCLUSION

In this paper, we have presented analytical studies of the OBS scheme using the system approximation technique. We modeled the OBS scheme into a SSQ, precisely, a state dependent $E_j/E_k/1/n$ queue, and then analyzed the throughput and delay performances of the system. We have again confirmed the performance advantage of our earlier proposed OBS scheme for high speed WLANs. Additionally, we studied the throughput optimization of the OBS scheme, which provides a mean for optimal network design should the OBS scheme be implemented in a high speed WLAN. Simulation experiments were then carried which have validated our employed approximation.

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