# Out-of-Band Signaling Scheme for High Speed Wireless LANs

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***Abstract*— In recent years, the physical layer data rate provided by 802.11 Wireless LANs has dramatically increased thanks to significant advances in the modulation and coding techniques employed. However, previous studies show that the 802.11 MAC operation, namely the Distributed Coordination Function (DCF), represents a limiting factor: the throughput efficiency drops as the channel bit rate increases, and a throughput upper limit does indeed exist when the channel bit rate goes to infinite high. These findings indicate that the performance of the DCF protocol will not be efficiently improved by merely increasing the channel bit rate. This paper shows that the DCF performance may significantly benefit from the adoption of two separate physical carriers: one devised to manage the channel access contention, and another devised to deliver information data. We propose a scheme, referred to as Out-of-Band Signaling (OBS), designed to reuse (and remain backward compatible with) the existing 802.11 *medium access control* (MAC) specification. Performance evaluation of OBS is carried out through analytical techniques validated via extensive simulation, for both saturation and statistical traffic conditions. Numerical results show that OBS improves the throughput/delay performance, and provides better bandwidth usage compared with the in-band signaling technique employed by DCF.**

***Index Terms*— Wireless LAN, IEEE 802.11, computer network performance.**

## I. Introduction

AMONG the various wireless technologies appeared in the last 15-20 years, perhaps 802.11 *wireless local area networks* (WLANs) [1] have shown the most rapid and notable increase in the achievable data transmission rate. Born as a WLAN standard for slow data rate applications (1 and 2 Mbps), the 802.11 physical layer specification has been dramatically enhanced well above the most optimistic initial plans. Building on the impressive market success of the 11 Mbps IEEE 802.11b [2] physical layer enhancement standardized in 1999 (and better known with its layman name Wi-Fi, inherited by the relevant interoperability certification), today most of the deployed network interface cards and access points comply with the IEEE 802.11a/b/g specifications, and hence support bit rates up to 54 Mbps in both the 2.4 GHz (IEEE 802.11g [3]) and the 5 GHz ISM band (IEEE 802.11a [4]).

In the last few years, several proprietary solutions have been offered by a multiplicity of vendors to support bit rates up to 108 Mbps and beyond. The pressuring demand for higher capacity, the promising and successful adoption of breakthrough multiple-input multiple-output (MIMO) technologies, and the need to develop interoperable products, have fostered IEEE to form, in January 2004, a new Task Group, 802.11n [5], chartered to develop a new high data rate amendment to the 802.11 standard. From the original 100 Mbps goal, the 802.11n targeted maximum data rate has been continuously increased during the task group n activities, to as much as the current "beyond 500 Mbps" targets (and with a not so unrealistic sight towards the Gbps barrier).

However, even impressive advances in terms of physical rate are insufficient, by themselves, to increase the performance experienced by the end users. In fact, the 802.11 *medium access control* (MAC) protocol introduces severe overheads which significantly reduce the throughput experienced at the MAC Service Access Point (SAP) interface. For example, it is straightforward to show that, with 802.11b, the maximum throughput achievable at the MAC layer is typically[1] of the order of 6-7 Mbps. Indeed, Xiao and Rosdahl [6] have shown that the performance of the IEEE 802.11 MAC protocol drops as the channel bit rate grows, and that a somewhat surprisingly small throughput upper limit (e.g., in the order of 50 Mbps for 802.11a with 1000 bytes payload sizes) does exist when the channel bit rate goes to infinity.

These findings demonstrate that the performance of a WLAN is significantly limited by the mechanisms employed to control the access to the shared medium, and their related overhead. However, not only a complete re-design of the 802.11 MAC protocol is highly unrealistic, as it would impede backward compatibility with legacy devices, but also amendments of the MAC operation should be designed with great care, and should be devised to reuse as much as possible the MAC primitives already deployed in the existing protocol stacks.

The goal of this paper is to show that a simple way to increase the performance of a high speed WLAN is to employ two distinct carriers, one *data channel* devised to deliver the actual information data, and another channel, referred to

[1]Actually, the precise value depends on the payload size and on some physical layer parameters. For example, straightforward computation shows that with 1470 bytes application layer datagrams encapsulated in UDP/IP packets, and 192 $\mu s$ long PLCP preamble, the application-layer throughput perceived by a single user on an ideal 802.11b WLAN employing the DCF basic access method is only 6.107 Mbps. Almost all the overhead is indeed due to the 802.11 MAC operation. In fact the throughput experienced at the MAC sub-layer rather than at application-layer, i.e. considering the UDP/IP 28 header bytes, plus the 8 bytes LLC-SNAP encapsulation as "useful" data, is only marginally greater (6.257 Mbps).

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as *signaling channel*, devised to manage the channel access contention. Our proposed approach, referred to as Out-of-Band Signaling (OBS), relies on standard-compliant mechanisms. The signaling channel is in fact managed with a procedure identical to the RTS/CTS handshake, while the data channel is governed by the traditional procedures and control frames developed for the Point Coordination Function (PCF) specified in the 802.11 standard. 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 additional bandwidth required for the signaling channel; hence, the overall system performance is improved.

The rest of this paper is organized as follows. Section II revisits related work presented in the literature. Section III briefly reviews the IEEE 802.11 MAC protocol, and describes how the protocol is adapted to operate within the proposed OBS scheme. In Sections IV and V, we analyze the performance of the OBS scheme under saturation condition and discuss the results, respectively. Section VI provides analysis and performance results of OBS scheme under statistical traffic. Conclusions are drawn in Section VII.

## II. Related Work

Since the release of the IEEE 802.11 standard, several efforts have been made to improve its performance. One commonly employed strategy is the improvement of the contention resolution mechanism and the related backoff operation, in order to achieve a higher protocol efficiency. Some examples employing this strategy are given as follows. Cali *et al.* [7] propose an adaptive backoff mechanism devised to overcome the performance impairments that the standard "static" 802.11 backoff mechanism encounters in congestion situations, i.e. when the default contention window settings are shown to be suboptimal. Wang *et al.* [8] propose to slowly reduce the contention window value when frames are successfully transmitted. This leads to a less aggressive channel access behavior which in turns results in lower steady-state collision probabilities. Choi *et al.* [9] introduce a reservation scheme, where each station broadcasts its future backoff information on a successful transmission to avoid others from colliding with its scheduled transmission in the future.

Another approach to improve protocol performance is the minimization of the per-packet overheads due to overheads of protocol headers. Xiao [10] analyzes the efficiency of burst transmissions[2], frame concatenation and packing. Similar concepts are being discussed in [5], where the MAC acknowledgments are aggregated into a single *block ack* as in [11]. Finally, in [12] the same TXOP is used for bi-directional traffic, thus allowing a receiver to send back a frame burst to its sender before performing the block ack transmission.

In infrastructure networks, the usage of centralized scheduling algorithms deployed on top of extended versions of the PCF is also a viable approach to improve performance. For example, Ganz and Phonphoem [13] propose the use of superpoll instead of single poll to better utilize the channel. The access point polls multiple stations in one transmission with indication of the transmission order of polled stations. In [14], Lo *et al.* introduce CP-Multipoll where the access point broadcasts the backoff counters of all polled stations for efficient transmission scheduling. Lim *et al.* [15] propose a polling mechanism where the AP first polls the stations to notify data transmissions occurring on a separate channel. After receiving the queue information from the stations, the AP uses superpoll to poll the stations for the frame transmissions.

A rather different strategy to increase the performance of WLANs is the multichannel approach which allows the MAC protocol to simultaneously access multiple channels. There are two commonly considered methods in this strategy, namely, the aggregation of multiple orthogonal channels into a single high data rate channel for operation, and management of multiple orthogonal channels for independent operation. Authors in [16] employ the former method where two 20 MHz OFDM channels are aggregated into a single 40 MHz channel with backward compatibility consideration. However, as studied in [6], such an aggregation does not overcome the MAC overhead limits and therefore does not improve the asymptotic protocol efficiency. The latter method that considers management of multiple orthogonal channels has received increasing attention in the recent literature, especially in the area of multi-hop WLAN networks. Nasipuri *et al.* [17] propose a soft channel reservation scheme where each station listens simultaneously to all the channels, and on a per-packet basis, selects the least congested channel for transmission. This scheme has been simplified in [18], in which a dedicated common channel is introduced for broadcasting control messages. Furthermore, the authors of [19] propose the use of fixed time intervals for control message exchange within a selected data channel to reduce control message overheads.

The scheme proposed in this paper falls under the strategy of multichannel approaches. However, unlike previous work in this area mainly devised to improve the performance of multi-hop networks, in this paper we show that the availability of two separate channels, one for resource reservation (i.e. signaling) and the other for actual data delivery, indeed improves the performance of a single-hop WLAN. The uniqueness of our scheme is the combination of asymmetric dual-channel, random access reservation and a polling mechanism for data transmission that minimizes protocol overheads. Our early protocol ideas and a preliminary performance investigation through analytical modeling were presented in the conference works [20] and [21], respectively. In this paper, we significantly revise and extend these earlier works, specifically i) we provide a deeper understanding of the OBS operation and effectiveness; ii) we extend the relevant performance evaluation; iii) we provide a refined and more detailed analytical modeling of the DCF backoff operation, and iv) we extend the study of the OBS performance to the case of statistical traffic (i.e. non saturation operation).

## III. Out-of-Band Signaling Scheme

Rather than being a new MAC proposal for high speed Wireless LANs, the OBS scheme is devised to operate, with minimal and backward-compatible modifications, the traditional IEEE 802.11 MAC mechanisms (specifically the

[2]This is known as *Transmission Opportunity* TXOP in the standard.

Distributed Coordination Function - DCF - and the Point Coordination Function - PCF) over two separate carriers. One low bit rate channel is devised to manage the contention to access the shared medium, while a second high bit rate contention-less channel is devised to deliver data frames. After a very brief review of the basic principles of DCF and PCF (the reader interested in additional details may refer to [1]), this section follows up by describing the proposed OBS operation.

### A. Distributed Coordination Function - DCF

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

The basic access method 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 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 station to detect transmission from 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 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* (ACK) frame after a *short interframe space* (SIFS). If the sender does not receive the ACK frame 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 specified backoff rules. Additionally, the standard specifies that the frame will be dropped after a certain number of retransmissions.

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 specified backoff technique. The sender transmits a special RTS frame when its backoff counter reaches zero. 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 when large frames are transmitted, as it reduces the duration involved in transmission collisions.

### 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 commands issued by a "Point Coordinator" (PC), which coincides with the Access Point (AP) in infrastructure networks; hence, it is contention free. The AP uses *point coordination interframe space* (PIFS) when issuing polls. The PIFS is longer than SIFS but shorter than DIFS, hence the AP 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

OBS utilizes two different physical channels in a WLAN, where one channel is operating at a low bit rate for channel assignment purposes, and another channel is operating at a high bit rate for the actual data transmissions. We shall refer to these low and high bit rate channels as the "signaling" and "data" channels, respectively.

In what follows, we shall describe the OBS operation assuming that a reservation is performed for each *single* frame to be transmitted (as discussed later in this section, the proposed protocol can be significantly enhanced by performing a reservation for several data frames). When a station is ready for the transmission of a data frame, it transmits a *Request For Transmission* (RFT) frame using the IEEE 802.11 basic access method on the signaling channel. The RFT frame is basically an IEEE 802.11 MAC control frame that uses one of the unallocated frame type in the IEEE 802.11 standard. We set the length of the RFT frame to be equal to the length of RTS frame in the RTS/CTS method. When the AP receives the RFT frame, it acknowledges the request and schedules the data transmission on the data channel. Such a data transmission occurs through the standard PCF operation, and Poll+ACK frame are thus used for consecutive frame transmissions, to reduce the overhead of polling. Note that the transmission of the data frame may occur either right after the end of the RFT/ACK handshake, or after an arbitrary time delay. Fig. 1 illustrates the operation of the OBS scheme.

The basic idea behind the OBS scheme is that, in the DCF basic access method, transmission collision is the main overhead of data transmissions. While the collision overhead might be significantly reduced by the RTS/CTS operation, due to the shorter length of the actual colliding frames, the extra overhead introduced by the transmission of the RTS and CTS control frames is a significant penalty, especially when the channel data rate increases. By separating the contention and the actual data transmission onto two different channels, and using the low bit rate channel for the contention while dedicating the high bit rate channel to data transmissions, the costly transmission collisions, as well as the idle periods, can be avoided entirely on the high bit rate channel. Additionally, the use of short RTS/CTS-like frames for contention control over the signalling channel is effective in reducing collision overhead without incurring any significant overhead due to the signalling channel lower rate. Thus, this separation mechanism will improve the overall performance of WLANs.

The use of the OBS scheme also brings other advantages to WLANs. The first immediate benefit of OBS is its flexibility in terms of transmission scheduling. The AP in fact collects requests from stations on the signaling channel, but is not committed to follow up with the relevant data frame transmission in the same order. This allows the deployment of scheduling approaches devised to provide service differentiation based on requested quality of service (QoS) and the network setting. A possible mechanism to achieve such service differentiation is the introduction of fair queueing algorithm such as *Deficit Round Robin* (DRR) [22] to ensure fairness or provide rate differentiation among stations.

Additionally, any improvement to the PCF protocol is applicable to OBS. Some examples include the combination of ACK or Poll frames with data frames, and use of superpoll [13] which further reduce transmission overheads. Moreover, as in any reservation-polling scheme, another significant benefit of OBS is the ability to use a single reservation occurring on the signaling channel for the transmission of multiple data frames or the set-up of a virtual circuit; thus significantly reducing the relative overhead of the reservation handshake.

Furthermore, an important characteristic designed on purpose in our OBS proposal is the backward compatibility with the current IEEE 802.11 standard. In principle, each of the two OBS channels, namely signaling and data, may be shared with legacy DCF stations. In fact, the signaling channel relies on the DCF operation (where the data frame is substituted, for OBS stations, with the RFT frame), while the data channel relies on standard PCF, which is meant to be deployed on top of the DCF operation (the point coordinator reserves the channel by using a PIFS as inter frame space, as briefly reviewed in the previous section). More specifically, we deem convenient to deploy a dedicated low rate signaling channel from free available spectrum[3], while the data channel can be deployed using a standard IEEE 802.11a/b/g channel, and can be shared with legacy DCF stations. Note that the data channel sharing is ultimately controlled by the OBS operation, as the duration of the PCF super frame is determined by OBS, and may be dynamically adapted to the amount of traffic offered by the OBS stations. Clearly, if we dedicate longer PCF super frame to OBS data stations, we are left with lower amount of resources to dedicate to legacy DCF stations. Arbitrary policies may be considered to balance the channel sharing between legacy and OBS stations: depending on the policy employed, differences in experienced performance may arise between these two classes of stations.

[3]The low bit rate channel has a maximum bit rate that is lower than the data channel bit rate; Considering the same modulation technique for wireless transmission for both channels, a 12 Mbps signaling channel requires about 20% of the spectrum allocated for a 54 Mbps channel in IEEE 802.11a. Similar to the data channel, the bit rate for the signaling channel can be lowered by link adaptation algorithm because of distance or noise.

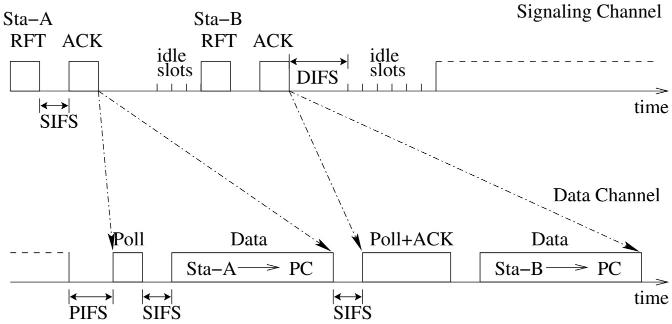


Fig. 1. The OBS scheme illustrated.

## IV. Saturation Analysis of Out-of-Band Signaling Scheme

In this section, we describe the analytical model developed for the study of the OBS scheme. In the proposed analysis, we assume (worst case) that every frame transmission undergoes an explicit reservation through the signaling channel. In other words, we do not account for the possibility of a station to inform the AP that one or more additional frames are queued.

In general, a station may be found in three possible states. We define:

- *Ready state*: the station is currently scheduling its RFT transmission on the signaling channel;
- *Backlogged state*: the station is currently waiting for a poll message from the AP on the data channel;
- *Idle state*: the station has no frames available for transmission.

A station switches from idle to ready when a frame arrives into its local buffer. Then the transition from ready to backlogged occurs when the station successfully exchanges the RFT/ACK message with the AP, and thus waits for a Poll command to be received on the data channel. When the data frame is successfully transmitted, the station either returns to the idle state, if no more frames are available in the local buffer, or to the ready state if one or more frames are buffered for transmission. The assumption of saturation [23] conditions therefore implies that the station will only alternate between ready and backlogged state.

The model proposed in what follows builds on the Markovian Framework modeling technique presented in [24]. The key idea is to model the number of stations in the backlogged state, i.e. waiting for a Polling command from the AP or engaged in the transmission of the data frame, with a *single server queue* (SSQ). An arrival to the SSQ occurs when a station switches from the ready to the backlogged state, i.e. when the station successfully completes an RFT/ACK handshake on the signaling channel. A departure from the SSQ occurs when a data frame is successfully transmitted and thus the station re-enters (owing to the assumption of saturation conditions) the ready state.

Assume now that the total number of stations in the network is $n$. Let $m$ be the (time varying) number of backlogged stations, i.e. the number of stations waiting in the SSQ. Hence, the number of stations in the ready state is $n-m$. This remark allows to model the arrival process to the SSQ with a state-dependent arrival rate $\lambda_{n-m}$, being the rate of a successful

RFT/ACK message exchange conditioned to the fact that $n-m$ ready stations are competing to access the signaling channel. In fact, a success of such an exchange generates a new backlogged station, i.e., a new arrival to the SSQ. Hence, the arrival process of the SSQ is the service process of the signaling channel. The SSQ service rate $\mu$ is independent of the SSQ state. In order to complete the model, we need to i) determine the arrival rate $\lambda_{n-m}$ for all the possible values $m$, and ii) model the SSQ queueing system with proper assumptions on the arrival and departure process statistics (for which a Poisson approximation is clearly unrealistic). These two issues are separately tackled in the next two subsections.

### A. SSQ arrival rate computation

By model construction, the arrival rate to the SSQ is equal to the service rate of the signaling channel, i.e. the rate at which successful RFT/ACK handshakes occur. As it will be demonstrated by the comparison between analytical and simulation results, a good approximation is to compute $\lambda_{n-m}$ as the steady-state service rate of an 802.11 DCF network with $n-m$ stations. This computation can be easily accomplished by applying the well known throughput analysis proposed for the IEEE 802.11 DCF protocol starting from [23], and adapting the analysis to the DCF basic access method corresponding to the exchange of the RFT and the relevant ACK frames (remember that the rest of the handshake, namely the data frame exchange, occurs on the data channel and thus is separately modeled).

In more details, in this paper we rely on the more general modeling framework proposed in [25], which allows to take into account retransmission limits (first developed in [26]) as well as a large class of more general backoff schemes (although this latter feature is of no specific interest in this paper). From [25], we can jointly compute the probability $\tau$ that a station transmits in a randomly chosen slot, and the probability $p$ that a transmitting station (among $n-m$ ready stations) experiences a collision, by solving the following system of two non-linear equations:

$$\tau = \frac{1}{1+\frac{1-p}{1-p^{R+1}}\sum_{i=0}^{R} p^i E[b_i]} \quad (1)$$

$$p = 1-(1-\tau)^{(n-m)-1} \quad (2)$$

where $R$ is the retransmission limit, i.e. the maximum number of retries after which a frame is dropped, and $E[b_i]$ is the sequence of mean backoff values employed at each backoff stage $i$. Since standard DCF is employed, in our first approximation[4],

$$E[b_i] = \frac{\min(2^i(CW_{\min}+1)-1, CW_{\max})}{2}, \ i=1,2,\ldots,R. \quad (3)$$

[4]In this formula, as well as in the following throughput formula, for simplicity of presentation, we neglect the issue discussed in [25], [27] concerning the different access probabilities experienced by the transmitting and the listening stations for what concerns the slot immediately following a transmitted frame in Legacy DCF (this problem has been amended in the 802.11e new specification of the backoff counter decrement). Indeed, its impact in terms of numerical accuracy is marginal if standard 802.11a/b/g DCF parameters are employed.

From the values $p$ and $\tau$, the service rate $\lambda_{n-m}$ is readily computed [23], [25] as the IEEE 802.11 DCF channel throughput measured in frames per second, i.e.

$$\lambda_{n-m} = \frac{P_s P_{tr}}{(1-P_{tr})\sigma + P_{tr}P_s T_s + P_{tr}(1-P_s)T_c} \quad (4)$$

where $\sigma$ is the length of a slot time, $P_{tr} = 1-(1-\tau)^{(n-m)}$ is the probability that there is at least one transmission in the considered slot time, $P_s = (n-m)\tau(1-\tau)^{n-m-1}/P_{tr}$ is the probability that a transmission occurring on the channel is successful, and $T_s$ and $T_c$ are the average successful transmission slot time and the average collision slot time, given by [23]

$$\begin{cases} T_s = RFT + SIFS + \delta + ACK + DIFS + \delta \\ T_c = RFT + DIFS + \delta \end{cases}. \quad (5)$$

### B. Queueing model for the SSQ

Knowing that the signaling channel operates the basic access method of the IEEE 802.11 MAC protocol, and according to [24], the service time distribution of the IEEE 802.11 MAC protocol can be accurately described by an appropriate Erlang distribution under saturation load condition[5], then the interarrival time of the SSQ can be accurately modeled by an Erlang distribution.

We adopt the usual assumption in the MAC protocol performance analysis that the frame size is constant. As a result, the protocol service time distribution on the data channel is deterministic. In the Markovian Framework, this distribution can be approximated by an Erlang distribution due to its small variance characteristics [24]. Consequently, we construct a state dependent $E_j/E_k/1/n$ (SD-$E_j/E_k/1/n$) queue to model the OBS scheme, where $E_j$ and $E_k$ indicate the Erlang distributions with $j$ and $k$ stages, respectively. The arrival rate of our SSQ is state dependent because different numbers of ready stations require different time periods to obtain a successful RFT/ACK message exchange on the signaling channel[6].

The service rate of the SSQ, $\mu$, is given by

$$\mu = 1/T_{cycle}, \quad (6)$$

where the $T_{cycle}$ is the period of a polling cycle, which can be expressed as

$$T_{cycle} = POLL + SIFS + \delta + T_{DATA} + SIFS + \delta. \quad (7)$$

The balance equation set of the SSQ model is provided in Appendix I. The Markov Chain state $\{x, y, z\}$ denotes the situation that the SSQ has $x$ backlogged stations, and the SSQ is in the Erlang arrival stage $y$ and Erlang service stage $z$. We compute the stationary probabilities of the SD-$E_j/E_k/1/n$ queue with $j=16$ and $k=32$. These settings are chosen based on the study given in [24] and [28].

[5]While [24] shows the result using simulation study, in [28] we have performed a comprehensive analytical study on the service characteristics of the IEEE 802.11 MAC protocol showing that it is possible to find an Erlang distribution that shares the same statistical characteristics with the service time distribution of the IEEE 802.11 MAC protocol.

[6]The duration difference is caused by the employed contention protocol; generally higher number of stations requires longer time to resolve the contention as more collisions will occur.

Let $p_i$ be the probability that there are $i$ backlogged stations in the network, where $i = 0, 1, \ldots, n$. Relating to the SSQ, $p_i = \sum_{y,z} \pi_{i,y,z}$, where $\pi_{i,y,z}$ is the steady state probability of the SSQ being in state $\{i, y, z\}$. The mean arrival rate of the SSQ, $\overline{\lambda}$, can be computed by

$$\overline{\lambda} = \sum_{i=0}^{n} (\lambda_{n-i} \cdot p_i), \tag{8}$$

and the system throughput, $\gamma$, can be obtained by

$$\gamma = \overline{\lambda} \cdot d_p, \tag{9}$$

where $d_p$ is the average size of the payload in a frame.

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

$$\overline{m} = \sum_{i=0}^{n} (i \cdot p_i). \tag{10}$$

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

$$W_q = \overline{m} / \overline{\lambda}. \tag{11}$$

The average queuing delay corresponds to the time period between a successful RFT/ACK message exchange and the frame transmission time. This queuing delay time does not include the time period of the contention and RFT/ACK message transmission on the signaling channel.

To compute the transmission delay, we first derive the average number of ready stations, adjusted for frames dropped due to retry limit. The mean number of ready stations, $E[n_s]$, is given by

$$E[n_s] = \sum_{i=0}^{n} (n-i) \left[1 - P(pck\ drop)_{n-i}\right] \cdot p_i, \tag{12}$$

where $P(pck\ drop)$, given in [25], is the probability that a station will drop its frame due to retry limit; the variable $n-i$ is the number of ready stations. The probability $P(pck\ drop)$ is computed by

$$P(pck\ drop) = \tau(1-p) \frac{p^{R+1}}{1-p^{R+1}} \sum_{i=0}^{R} (1 + E[b_i]). \tag{13}$$

Having $E[n_s]$, the average signaling delay, $W_{sig}$, is computed through Little's formula, which gives

$$W_{sig} = E[n_s] / \overline{\lambda}. \tag{14}$$

The mean MAC transmission delay of OBS is simply the sum of the queueing delay and the signaling delay:

$$W_s = W_{sig} + W_q. \tag{15}$$

## V. Saturation Performance of OBS

To illustrate the effectiveness of the OBS scheme, its performance is compared with that of the existing IEEE 802.11 MAC protocol. We first report and discuss saturation throughput and delay results, which are useful to understand the protocol performance in high load conditions. Then, we follow up with the optimization of the OBS performance in the same saturation conditions.

TABLE I
IEEE 802.11a parameters.

| | |
|---|---|
| Slot Time | $9\mu s$ |
| SIFS | $16\mu s$ |
| DIFS | $34\mu s$ |
| PIFS | $25\mu s$ |
| Preamble Length | $20\mu s$ |
| Propagation Delay ($\delta$) | $1\mu s$ |
| $CW_{min}$ | 16 |
| $CW_{max}$ | 1024 |
| Retry Limit (long) | 7 |

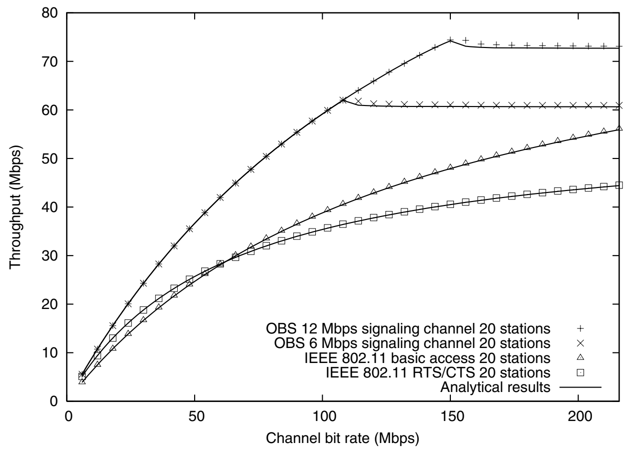


Fig. 2. Saturation throughput with various data channel bit rate.

Unless otherwise specified, in the rest of this section we use constant MAC frames each carrying a 1500 bytes payload. As mentioned in Section III, in the analysis we require OBS to enforce an RFT/ACK handshake for each single data frame to be transmitted. We rely on the physical layer parameters of the IEEE 802.11a [4] (reported for the convenience of the reader in Table I). As a general graphic notation, the symbols shown in the figures represent simulation results, while the solid lines plot analytical results. The analytical results for the IEEE 802.11 schemes (basic access and RTS/CTS) are computed according to the model presented in [25].

### A. Performance Comparison

Fig. 2 shows the saturation throughput, in Mbps, versus a varying data channel bit rate employed by the OBS scheme, ranging from a few Mbps up to more than 200 Mbps. Two different OBS signaling channel rates, namely 6 and 12 Mbps, are assessed. In the following, we refer to an OBS scheme using an x Mbps signaling channel with the synthetic notation $\text{OBS}_\text{x}$. For comparison purposes, results for both the DCF access methods (basic and RTS/CTS) are also reported. The number of stations in the figure is fixed and set to 20.

From Fig. 2, several important considerations can be drawn. Firstly, the figure shows an excellent match between our proposed analytical framework and the simulation results for the OBS scheme, which confirms the accuracy of our analysis.

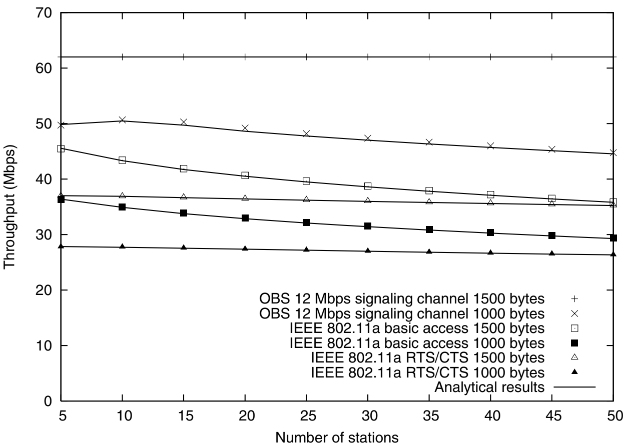


Fig. 3. Saturation throughput with 108 Mbps channel bit rate.

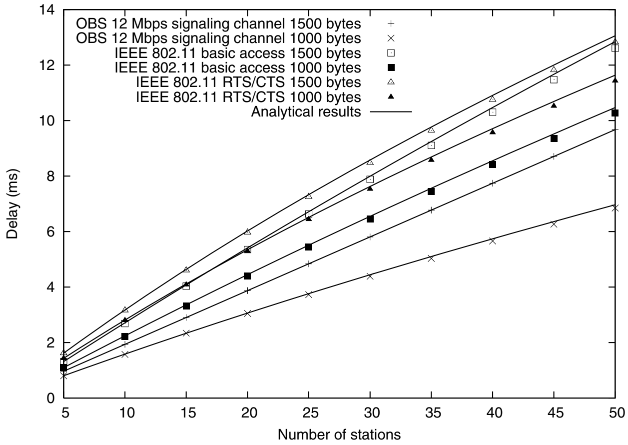


Fig. 4. Mean saturation transmission delay with 108 Mbps channel bit rate.

Secondly, Fig. 2 allows the comparison of the OBS performance with that achieved by the 802.11 access methods. From the figure, we see that $OBS_{12}$ can provide a maximum saturation throughput of almost 75 Mbps from a 150 Mbps data channel. For comparison, the IEEE 802.11 basic access method only achieves 50 Mbps throughput from a 150 Mbps data channel. Since OBS requires an additional of 12 Mbps signaling channel, the total usage of the bandwidth is the bandwidth combination of the two OBS channels, which gives 162 Mbps. If this were the bit rate of the IEEE 802.11 basic access method, as can be seen from Fig. 2, its throughput would still be just around 50 Mbps, which remains below the performance of the OBS scheme. A similar comparison can be carried out for various data rates reported in the figure, and shows that OBS performance consistently outperforms both legacy DCF access methods[7]. This shows that the use of the signaling channel in OBS allows a higher utilization in the data channel. Comparing to the existing IEEE 802.11 schemes, the throughput gain in the data channel for OBS exceeds the additional bandwidth required for the signaling channel.

Thirdly, and perhaps more descriptive of the OBS operation, Fig. 2 shows that, for the same data channel rate, a difference between the performance of $OBS_6$ and $OBS_{12}$ emerges only as long as the data channel rate increases above a given threshold. Specifically, when the data channel is below about 100 Mbps, $OBS_6$ and $OBS_{12}$ achieve identical throughput performance. Above this threshold, $OBS_6$ performance flattens out, while $OBS_{12}$ performance further increases until the data channel rate reaches about 150 Mbps. The reason behind this behavior will be discussed in more details in the next subsection V-B.

In order to assess the OBS performance for a varying number of stations, and compare it with that achieved by the legacy 802.11 access methods, Fig. 3 reports the OBS saturation throughput versus the number of stations, for a data channel rate set to 108 Mbps (i.e., the double of the current maximum channel bit rate of IEEE 802.11a and g), and a signaling channel rate set to 12 Mbps. Although OBS requires an additional 12 Mbps bandwidth for the signaling channel, the comparison presented in Fig. 3 nevertheless shows that OBS throughput advantage exceeds the 12 Mbps employed for such a signaling channel. Moreover, the performance advantage is indeed considerable as we recall that the DCF would not be capable of converting all this extra 12 Mbps bandwidth available into throughput performance (as clearly shown and discussed previously in Fig. 2).

Moreover, Fig. 3 shows that OBS, similar to the 802.11 RTS/CTS method and unlike the basic access method, holds the important property that throughput performance is marginally dependent on the number of competing stations. This suggests that, similarly to those demonstrated by literature work for RTS/CTS [23], OBS is also loosely dependent on the employed MAC parameter settings, e.g. a too small setting of the $CW_{\min}$ parameter when a large number of stations compete does not cause throughput degradation. However, the figure shows that OBS does not exhibit a decrease in performance such as what happens for RTS/CTS when the channel bit rate increases.

Furthermore, Fig. 3 shows the OBS performance for smaller payloads (1000 bytes). As expected, the performance advantage decreases with a smaller payload, as the savings introduced in a reduced collision overhead are lower than the case of a large frame payload. Nevertheless, the performance advantage of OBS over legacy DCF remains notable also in this case.

Finally, we conclude this section by reporting delay performance. Fig. 4 plots the mean MAC transmission delay of the OBS scheme compared with the IEEE 802.11 schemes for various numbers of competing stations. With a frame size of 1000 bytes, OBS maintains a MAC transmission delay of 8.9 ms even with 50 stations under saturation load, thus outperforming the corresponding IEEE 802.11 delays of 15 ms and 13.4 ms for RTS/CTS and the basic access method, respectively. The immediate benefit of the lower transmission delay is a better support for delay-sensitive applications such as Voice over Internet Protocol (VoIP) or video conferencing[8].

[7]The only apparent exception is for very low channel data rates, where clearly a 6 Mbps signaling channel rate reported in the figure is over-dimensioned with the actual data channel needs.

[8]These applications in any case would furthermore dramatically benefit from the ability to reserve the data channel access once per flow rather than once per data frame.

### B. OBS Performance Discussion

Fig. 2 suggests that the OBS performance is the result of a compromise between signaling channel effectiveness and data channel throughput. In fact, as discussed before, the performance of the OBS scheme increases steadily at low data channel bit rate region, it then stays relatively flat at high data channel bit rate. Most importantly, the throughput value at the point where OBS performance flattens out heavily depends on the signaling channel bandwidth.

The intuitive reason behind this behavior can be described as follows. In the low data channel bit rate region, the data channel is always fully utilized with data transmission, and the limit of the throughput is mainly bounded by the transmission overhead caused by the PCF operation (i.e., physical preambles, polls, positive acknowledgment, inter-frame spaces). Hence with higher bit rate on the data channel, higher throughput is achieved. At the turning point from the increasing trend to the flat trend, the successful requests from the signaling channel are just enough to saturate the data channel, thus the increment of the data channel bit rate beyond the turning point does not elevate the throughput performance further.

This intuitive reason can be more formally supported as follows. Consider a spectrum that allows a channel to operate at data rate $R$. For OBS, this spectrum may be split into two independent channels operating at $R_{data}$ and $R_{sig}$ where $R_{data} + R_{sig} \leq R$ due to the spectral splitting overhead. Because of the different rates and access rules, the maximum throughput in frames per second on the two OBS channels is generally different. Specifically, the signaling channel is regulated by the DCF operation, where RFT/ACK handshakes occur instead of the traditional DATA/ACK handshakes.

For the sake of the following discussion, the signaling channel throughput $S_{sig}$ can be conveniently approximated, in frames per second, by (4) computed for a fixed number of competing stations $n$ (the approximation being the assumption of a constant $n$ rather than of a variable number of competing stations which is more correctly done throughout the analysis presented in Section IV).

Conversely, in the data channel there is a centralized scheduler and the maximum throughput $S_{data}$, measured in frames per second, is equal to

$$S_{data} = \frac{1}{H_{PCF} + F/R_{data}}, \quad (16)$$

where $H_{PCF}$ is the PCF transmission overhead, including the POLL+ACK frame, the physical overheads and the inter-frame spaces, and $F$ is the frame size.

The overall OBS data throughput is clearly the minimum between $S_{sig}$ and $S_{data}$. In fact, whenever the successful reservation rate is lower than the data channel throughput, the OBS throughput is bounded by the limited number of reserved transmissions. Conversely, when the reservation rate is greater than the data transmission rate, the latter becomes the performance limiting factor.

Fig. 5 graphically illustrates the signaling channel throughput $S_{sig}$ and the data channel throughput $S_{data}$ for the case of a fixed total rate $R$ subdivided between data and signaling channels. Both cases of $R = 54$ and $R = 108$ Mbps are considered. Specifically, the figure reports in the x-axis the rate $R_{sig}$ assigned to the signaling channel, which results in a rate $R_{data} = R - R_{sig}$ assigned to the data channel. For sake of comparison, the figure reports also the throughput, measured in frames per second, achieved by the DCF basic access method for both the $R = 54$ (about 2000 frames/second) and $R = 108$ (slightly above 3000 frames/seconds) Mbps channel rate cases. From the figure, we can draw two important conclusions. Firstly, the OBS throughput performance reaches the maximum whenever the data and control channel have the same throughput. Secondly, for both the $R = 54$ and $R = 108$ Mbps channel rate cases, there exists a large region, i.e. a large amount of signaling channel rate settings, where the OBS performance outperforms DCF (we remark that, unlike Fig. 2, this figure has been obtained in the assumption that the same total rate $R$ is available to both OBS and DCF schemes).

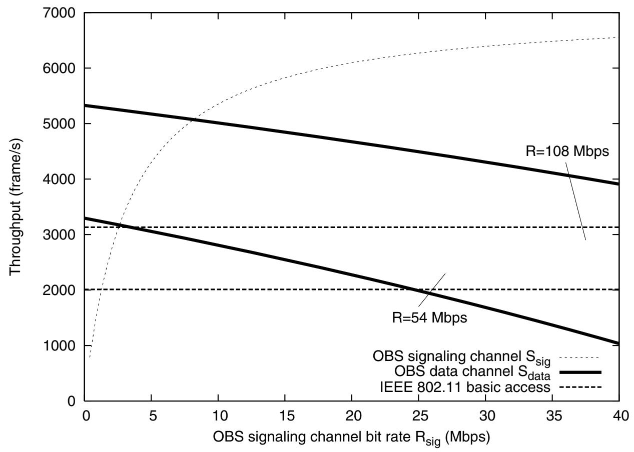


Fig. 5. Comparison of the OBS performance versus the DCF performance for a given overall bandwidth constraint.

### C. Signaling Channel Optimization

The throughput results plotted in Fig. 2 have shown that there exist a turning point in the OBS throughput performance such that OBS operates at its maximum throughput given a suitable pair of bit rates of signaling and data channels. From the discussion carried out in the previous section as well as from the related Fig. 5, it is now clear that such an optimum operation point is achieved when the signaling channel throughput equals to the data channel rate throughput.

To provide an exact computation (unlike the approximated treatment carried out in the previous descriptive section) of such an optimum operational point, it suffices to set the service rate of the RFT/ACK signaling channel handshake, $\overline{\lambda}$ as computed in (8), to be equal to the service rate $\mu$ of the data channel, provided by (6). More specifically, the quantity $\overline{\lambda}$ depends on the bit rate of the signaling channel and on the number of stations contending on the signaling channel, whereas the quantity $\mu$ depends on the bit rate of the data channel and the frame size. To be precise, the signaling channel bit rate affects $RFT$ in (5) which in turn affects (4) and $\overline{\lambda}$ in (8). Data channel bit rate influences $T_{DATA}$ which in turn influences $\mu$ in (6). For a given data channel rate, the optimal signaling channel rate which maximizes the OBS

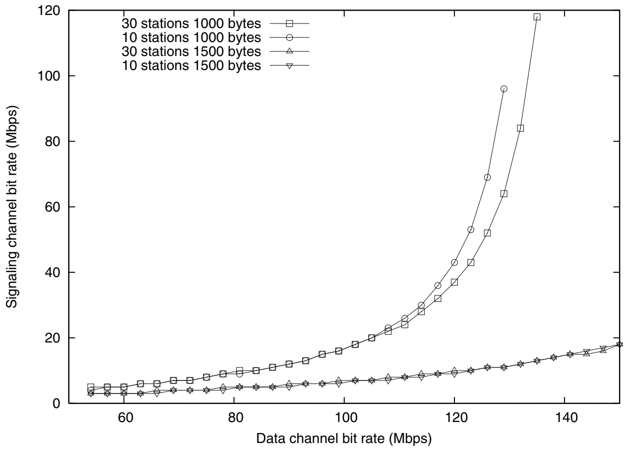


Fig. 6. Minimum signaling channel bit rate required to achieve full utilization on the data channel.

throughput is readily computed by imposing the condition $\overline{\lambda} = \mu$.

In Fig. 6, we show the bit rate pairs of signaling and data channels required to optimize the OBS operation. As can be seen, for the considered frame sizes, OBS requires relatively low bit rate signaling channel to fully utilize the data channel which is below 100 Mbps. Our particular interest here is the data channel of 108 Mbps bit rate. It is found that the signaling channel bit rate between 6 Mbps and 20 Mbps appears to be a good choice for commonly used frame sizes, and hence we consider 12 Mbps for the signaling channel bit rate for studies conducted in the previous subsections.

## VI. Analysis of the Out-of-Band Signaling Scheme under Statistical Traffic

The performance study of a protocol under saturated traffic load indicates the protocol performance under the extremely heavy load condition. However, the protocol often operates under non-saturated load conditions. It is thus important to also evaluate the performance of a protocol under non-saturation traffic, and here we focus on statistical traffic.

There are several approaches in modeling the IEEE 802.11 MAC protocol in the literature [24], [28]–[31]. The approach we consider for OBS performance study under non-saturation condition is the Markovian Framework presented in Section IV. We extend the Markovian Framework to capture the characteristics of statistical arrivals, and analyze the throughput and delay performance of OBS under the considered traffic. All analytical results are compared and validated by simulation.

### A. Markovian Framework for Out-of-Band Signaling Scheme under Statistical Traffic

We consider Poisson process with one frame buffer as arrival process for each station. In other words, each station holds only a frame in its local MAC buffer. Furthermore, we assume that the stations are statistically identical and independent. We reuse the definitions of *ready station*, *backlogged station*, and *idle station*, which are defined in Section IV. Under Poisson arrival, an *idle station* switches to a *ready station* when it generates a frame into its local buffer according to a Poisson process. A *ready station* switches to a *backlogged station* when it has successfully exchanged the RTS/CTS message with the AP. Under statistical traffic and one buffer assumption, a backlogged station switches to an idle station after its successful frame transmission on the data channel.

Applying Markovian Framework, we characterize the system with two queues in tandem. The first queue models the stage that a station switches from an idle station to a ready station indicating an arrival to the queue, and from a ready station to a backlogged station indicating a departure from the queue. The arrivals to this queue is an aggregation of arrivals from all idle stations, where the inter-arrival time has exponential distribution, and the aggregated arrival rate depends on the number of idle stations. The service process of the queue is the RFT/ACK frame exchange process, which, as described in the previous section, can be modeled by an Erlang distribution.

The departure of the first queue goes into the second queue. The second queue models the actual data transmission stage, that is, a backlogged station switching back to a ready station after its successful frame transmission. The arrival process of the second queue is the output process of the first queue, which has Erlang distribution. The service process of the second queue depends on the data frame size. For the constant frame size assumption, an Erlang distribution for service time is used as in the previous section.

Let the total number of stations in the network be $n$. Define $v$ to be the number of ready stations, then the number of idle stations is $n - v$. The arrival rate $\lambda_{n-v}$ is the state-dependent Poisson arrival process, which is given by

$$\lambda_{n-v} = (n - v) \cdot \hat{\lambda}, \tag{17}$$

where $\hat{\lambda}$ is the individual arrival rate of a station.

The service rate of the first queue, $\mu_1$, is the rate of a successful RFT/ACK message exchange when there are $v$ ready stations, which is given by (4). The service rate of the second queue, $\mu_2$, is the rate of frame transmission with polling scheme and constant frame size given by (6).

The balance equations set of the system is provided in Appendix II. The Markov Chain state $\{v, x, y, z\}$ denotes the situation that the system has $v$ ready stations and $x$ backlogged stations, and the system is in the Erlang service stages $y$ and $z$ of the first and second queues respectively. Similar with the previous section, we compute the stationary probability of the queue with $j = 16$ (the number of Erlang stages for the first queue), and $k = 32$ (the number of Erlang stages for the second queue).

Let $p_{v,x}$ be the probability that there are $v$ ready stations and $x$ backlogged stations in the network, where $v = 0, 1, \ldots, n$ and $x = 0, 1, \ldots, v$. Relating to the system, $p_{v,x} = \sum_{y,z} \pi_{v,x,y,z}$, where $\pi_{v,x,y,z}$ is the steady state probability of the system being in state $\{v, x, y, z\}$. The mean arrival rate of the system, $\overline{\lambda}$, can be computed by

$$\overline{\lambda} = \sum_{v=0}^{n} \left( \lambda_{n-v} \cdot \sum_{x=0}^{v} p_{v,x} \right), \tag{18}$$

and the system throughput, $\gamma$, can be obtained by

$$\gamma = \overline{\lambda} \cdot d_p, \quad (19)$$

where $d_p$ is the average size of the payload in a frame.

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

$$\overline{m} = \sum_{v=0}^{n} \sum_{x=0}^{v} (x \cdot p_{v,x}). \quad (20)$$

The computation of the mean MAC transmission delay is similar with that in the previous section (Equations (11)–(15)). Given the number of backlogged stations, $\overline{m}$, and the mean arrival rate, $\overline{\lambda}$, by Little's formula, we calculate the average queuing delay of a frame transmission, $W_q$, as

$$W_q = \overline{m}/\overline{\lambda}. \quad (21)$$

The mean number of ready stations is given by

$$E[n_s] = \sum_{v=0}^{n} \sum_{x=0}^{v} (v - x) \left[1 - P(pck\ drop)_{v-x}\right] \cdot p_{v,x}. \quad (22)$$

The mean signaling delay can be determined using Little's formula as

$$W_{sig} = E[n_s]/\overline{\lambda}. \quad (23)$$

The mean MAC transmission delay is simply the sum of the queuing delay and the signaling delay, which is

$$W_s = W_{sig} + W_q. \quad (24)$$

### B. Performance Comparison

Fig. 7 shows the mean transmission delay of the OBS scheme compared with the IEEE 802.11 schemes under statistical traffic. We use 12 Mbps signaling channel for the OBS scheme as justified in the previous section. Similarly, we use 108 Mbps data channel for the comparison. The symbols shown in the figures represent the simulation results, while the solid lines show the analytical results. Analytical results for the IEEE 802.11 schemes are computed using the model in [24], [28]. The results show that OBS has lower delay under medium to high load compared with the IEEE 802.11 schemes. Under very light load condition, all schemes perform similarly well where they offer mean MAC transmission delay of below 0.5 ms.

The throughput versus mean transmission delay of the OBS scheme is plotted in Fig. 8 and compared with the IEEE 802.11 schemes. OBS can achieve 57% throughput level, whereas IEEE 802.11 with basic access and RTS/CTS methods achieve 41% and 34% throughput level respectively. OBS also maintains delays lower than 1.6 ms, whereas IEEE 802.11 has delays up to 2.4 ms and 2.9 ms for basic access and RTS/CTS methods, respectively.

The results reported in the two figures verify the accuracy of our analytical framework. The figures show close match between the analysis and the simulation results. This analytical framework is useful for determining the number of application streams that can be supported by an access point (see for example [32]). It is also useful for admission control for quality of service demanding applications such as VoIP and video streaming.

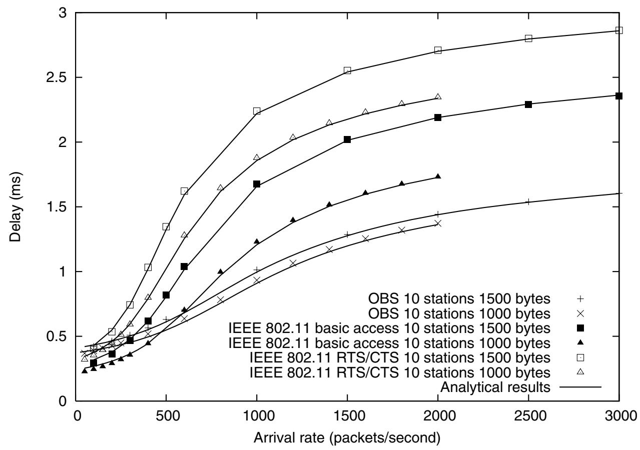


Fig. 7. Mean transmission delay under statistical traffic.

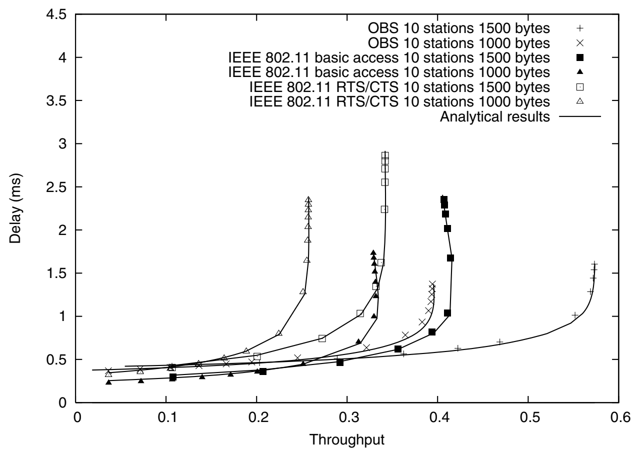


Fig. 8. Throughput versus mean transmission delay under statistical traffic.

## VII. Conclusion

In this paper, we have proposed and analyzed the OBS scheme for high speed WLANs. OBS uses a low bit rate channel for signaling and a high bit rate channel for the actual data transmission. We showed that the use of out-of-band signaling technique achieves higher overall throughput despite the need for an additional low bit rate channel for signaling. Besides, OBS maintains backward compatibility with the existing users of the IEEE 802.11 standards, where users of the IEEE 802.11 standards can access OBS WLANs, however, they will not enjoy the performance benefit.

To illustrate the performance advantage of OBS, we applied Markovian Framework to study the throughput and delay performance under the saturation load and the statistical traffic conditions. The analytical results, validated by simulation, indicated performance advantages of OBS compared with the current IEEE 802.11 schemes. We also investigated the channel bit rate settings for optimal performance in OBS, where we limit our study to the issue of protocol parameter design for the justification of OBS parameter selection.

## APPENDIX I
## BALANCE EQUATIONS OF OBS UNDER SATURATION CONDITION

For simplicity of formulation, let the invalid states of the Markov Chain model, i.e. state $\{x, y, z\}$ outside the range of $0 \leq x \leq n$, $0 \leq y < j$, and $0 \leq z < k$, has stationary probability of zero. We also assume that the arrival and service rates are zeros for out-of-range parameters i.e. the arrival rate is non-zero if $0 \leq x < n$ and the service rate is non-zero if $0 < x \leq n$. The balance equation set for the SSQ is given by

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

## APPENDIX II
## BALANCE EQUATIONS OF OBS UNDER STATISTICAL TRAFFIC

Similar with the previous section, let the invalid states of the Markov Chain model, i.e. state $\{v, x, y, z\}$ outside the range of $0 \leq v \leq n$, $0 \leq x \leq v$, $0 \leq y < j$, and $0 \leq z < k$, has stationary probability of zero. Assume that the arrival and service rates are zeros for out-of-range parameters i.e. the arrival rate $\lambda$ is non-zero if $0 \leq v < n$, the service rate $\mu_1$ is non-zero if $0 \leq x < v$, and the service rate $\mu_2$ is non-zero if $0 < x \leq v$. The balance equation set for the system is given by

$$\begin{aligned}
0 = & - \Big(\lambda_{n-v} + j\mu_1(v-x) + k\mu_2(x)\Big) P_{v,x,y,z} \\
& + \lambda_{v-1} P_{v-1,x,y,z} \\
& + j\mu_1(v-x) P_{v,x,y-1,z} + k\mu_2(x) P_{v,x,y,z-1} \\
0 = & - \Big(\lambda_{n-v} + j\mu_1(v-x) + k\mu_2(x)\Big) P_{v,x,0,z} \\
& + \lambda_{v-1} P_{v-1,x,0,z} \\
& + j\mu_1(v-x-1) P_{v,x-1,j-1,z} + k\mu_2(x) P_{v,x,0,z-1} \\
0 = & - \Big(\lambda_{n-v} + j\mu_1(v-x) + k\mu_2(x)\Big) P_{v,x,y,0} \\
& + \lambda_{v-1} P_{v-1,x,y,0} \\
& + j\mu_1(v-x) P_{v,x,y-1,0} + k\mu_2(x+1) P_{v+1,x+1,y,k-1} \\
0 = & - \Big(\lambda_{n-v} + j\mu_1(v-x) + k\mu_2(x)\Big) P_{v,x,0,0} \\
& + \lambda_{v-1} P_{v-1,x,0,0} \\
& + j\mu_1(v-x-1) P_{v,x-1,j-1,0} \\
& + k\mu_2(x+1) P_{v+1,x+1,0,k-1}.
\end{aligned}$$

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