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Performance Analysis of the IEEE 802.11 MAC Protocol

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ABSTRACT

This paper presents a new approach for performance evaluation of the IEEE 802.11 Medium Access Control (MAC) protocol. The approach is based on system approximations, where the statistical characteristics of the protocol operations are studied and approximated by an appropriate phase-type distribution. A queueing model that incorporates bursty arrival process as well as the statistical characteristics of the protocol operations is constructed. This model is used to study the performance of IEEE 802.11. The accuracy of the analytical results is verified by simulation.

1. INTRODUCTION

To provide an efficient and robust network in a wireless environment for a collection of mobile stations, the IEEE 802.11 working group has chosen the *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) protocol as the standard protocol for wireless *local area networks* (LANs). The CSMA/CA protocol is a random access protocol that is subjected to collisions. In the case of a collision, each mobile station executes the *Binary Exponential Backoff* (BEB) retransmission algorithm to resolve the collision and maintain the stability of the CSMA/CA channel.

The standardization of the IEEE 802.11 *Medium Access Control* (MAC) protocol has triggered significant research on the evaluation of its performance [2-5]. Performance evaluation of the IEEE 802.11 MAC protocol with all its details and under realistic traffic conditions has been considered difficult. Therefore, many analyses have assumed simpler traffic conditions such as Poisson sources with fixed size data frames [3,4], and/or simplifications of the protocol operations, for example, the simplification of the actual retransmission algorithm used in IEEE 802.11 [3-5]. As a result, the scope of the results of such performance analyses is somewhat limited.

Bianchi [2] has analyzed the IEEE 802.11 MAC protocol capturing all the protocol details. His performance evaluation assumes saturation traffic where by all stations are saturated, namely, they always have data frames to transmit. Since in the actual operation, the protocol rarely operates under such a traffic condition, it is of interest to evaluate the performance of IEEE 802.11 under statistical traffic conditions.

In this paper, we analyze the IEEE 802.11 MAC protocol without making simplifying assumptions on its details. We use a Markovian state dependent single server queue (SSQ) to accurately model the protocol for which the exact performance results are not readily obtainable. The arrival process of this SSQ represents the process of idle stations that become active. The statistical characteristics of the service time for a given queue size (number of active stations) are obtained by the saturation throughput analysis and can be fitted with an equivalent PH distribution, so that a Markovian state dependent SSQ structure can be used. Since the saturation throughput analysis of the IEEE 802.11 MAC protocol performed in [2] captures all the protocol details, by reusing the results from the saturation throughput analysis, the protocol details are retained.

In the next section, the operation of the IEEE 802.11 MAC protocol is revisited. In Section 3, we describe the model that we develop to analyze the performance. In Section 4 we obtain analytical results for performance evaluation for IEEE 802.11 under several traffic conditions and verify them by simulations.

2. THE IEEE 802.11 MAC PROTOCOL

According to IEEE 802.11, stations access the channel using a *basic access method*, or an optional *four-way handshaking access method* with an additional Request-To-Send/Clear-To-Send (RTS/CTS) message exchange (see Figure 1). Under the basic access method, a station, when ready for a new data frame transmission, first senses the channel status. If the channel is found to be busy, the station defers its transmission and continues to sense the channel until it is idle. After the channel is idle for a specified period of time called the distributed interframe space (DIFS) period, the station choose a random number as a backoff timer. Note that the time immediately after the DIFS period is slotted. As shown in Figure 1, the timeslot duration is at least the time required for a station to detect an idle channel plus the time required switching from listening to transmitting mode. The backoff timer is decreased by one for each idle slot, stopped if the channel is sensed busy, and then reactivated if the channel is idle again and remains idle for more than a DIFS time duration. When the backoff timer reaches zero, the data frame is transmitted.

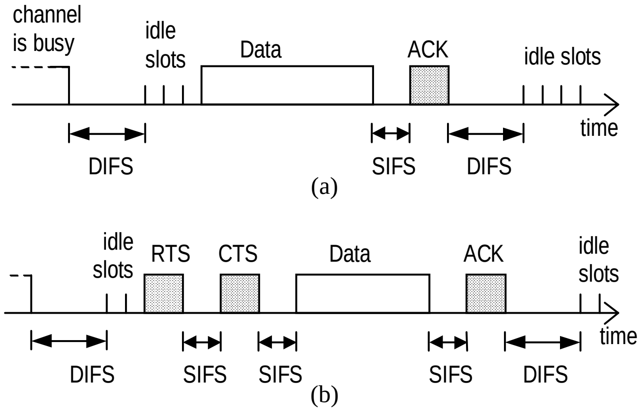

Figure 1: The IEEE 802.11 access methods: (a) Basic access method. (b) Four-way handshaking access method

The choice of the random number for the backoff timer is based on the binary exponential backoff algorithm, where a station chooses any of the numbers between 0 and *CW*-1 randomly with equal probability. The Contention Window (*CW*) is set to be *CWmin* for every new data frame transmission. *CW* is doubled each time when the transmission is unsuccessful, until it reaches *CWmax*, then it remains at *CWmax*. To determine whether a data frame transmission is successful, after its completion, a positive acknowledgement (ACK) is transmitted by the receiver. ACK is transmitted after a short interframe space (SIFS) period when successfully receiving the entire data frame. If ACK is not detected within a SIFS period after the completion of the data frame transmission, the transmission is assumed to be unsuccessful, and a retransmission is required.

In the four-way handshaking access method, an additional operation is introduced on top of the basic access method before a data frame transmission is taken place. When the backoff timer of a station reaches zero, instead of transmitting the data frame as in the basic access method, the station with the four-way handshaking access method first transmits an RTS frame to request for a transmission right. Upon receiving the RTS frame, the receiver replies with a CTS frame after a SIFS period. Once the RTS/CTS is exchanged successfully, the sender then transmits its data frame.

In the case where a sender wishes to transmit a message that is longer than the specified maximum IEEE 802.11 data frame size, the message must be fragmented before transmissions. The SIFS is used to provide an efficient transmission of the fragments of the message. As depicted in Figure 2, when the sender has seized the channel and transmitted the first fragment, it may continue to transmit the next fragment if an acknowledgement of the previous fragment is returned. The sender can continue to transmit its fragments until either it has completed all its fragments, or a predefined time period called the *dwell time boundary* [1] is reached.

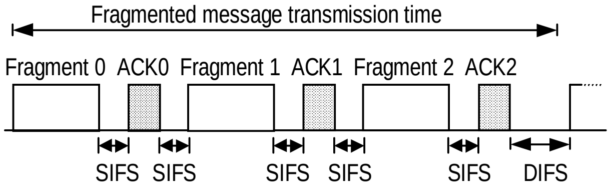

Figure 2: The IEEE 802.11 fragmentation operation

3. THE APPROACH

We consider a class of problems that, in general terms, can be defined as follows. Consider *k* stations sharing a transmission medium. They are fed by a certain arrival process and try to access the medium according to a given s protocol. The aim is to obtain numerical values for certain performance measures such as the mean transmission delay.

We begin by describing a saturation throughput analysis of the protocol, whereby we assume that there are only *i* stations sharing a transmission medium, $1 \le i \le k$, and all *i* stations are saturated so that whenever a station successfully transmits its data frame, the station is ready for another new data frame transmission immediately after the previous data frame is successfully transmitted. In other words, all *i* stations are always active. The main output from the analysis is the saturation throughput of the protocol given *i* saturated stations, $S(i)$.

From the saturation throughput, the mean service rate of a protocol given *i* active stations, $\mu(i)$, can be obtained by:

$$\mu(i) = \frac{S(i)}{t_d} \qquad (1)$$

where t_d is the mean duration of a payload transmission. In another words, $1/\mu(i)$ is the mean time between two successive successful data frame transmissions given *i* saturated stations. Notice that it is the sum of (i) the channel assignment time, and (ii) the mean duration of a data frame transmission which carries the payload.

To analyze the protocol under a statistical traffic, according to our approach, we construct a continuous time Markov chain single server queue (CTMC-SSQ) with a certain arrival and service processes. For the purpose of illustrating the approach, we consider a simple example of a CTMC-SSQ, the *state dependent* M/M/1/k (SD-M/M/1/k) queue. Under this model, there are *k* stations in a network. The *state* of the queue represents the number of active stations in the network. The number of active stations increases according to a Poisson process with parameter λ, and it decreases based on the state dependent service process. Both the arrival and service processes are memoryless in this case.

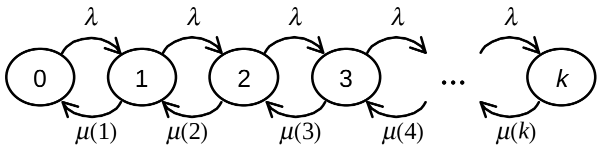

Figure 3: The state dependent service rates M/M/1/k queue for the analysis of a MAC protocol

From the saturation throughput analysis of [2], the mean service rate given *i* active stations is obtained and given by (1). Having non-zero active stations in IEEE 802.11 is, in fact, a temporary saturation condition, and therefore the results of the saturation analysis can be exploited. Since the state in the SD-M/M/1/k queue represents the number of active stations, together with the service rates obtained from the saturation throughput analysis, then the SD-M/M/1/k system can be used to analyze the protocol. Its transition state diagram is shown in Figure 3. The use of the SD-M/M/1/k system implies the assumption that the service time under saturation for any number of saturated stations is exponentially distributed. In many cases, this assumption may not be accurate. In such a case, a fitting of the statistical characteristics of the service time under saturation and service time of our CTMC-SSQ model is required, for each i where $1 \le i \le k$. To maintain the Markovian property, a PH distribution [6] (e.g. the Erlang distribution) could be used.

4. PERFORMANCE ANALYSIS

To analyze the protocols using our approach, we use the saturation throughput of IEEE 802.11 developed in [2]. In particular, the saturation throughput, $S(i)$, is given in Equation (13) in [2]. Having the saturation throughput, the service rate of the protocol, $\mu(i)$, can be calculated by (1). Here we follow the protocol model and assumptions made in [2] except that the input traffic is statistical instead of saturated.

We consider a finite population of mobile stations, k, within the same radio coverage area in an IEEE 802.11 network. Each station can be in one of two states: an idle state and an active state. A station is idle during the inter-burst period, so its transition between an idle and an active state is exponentially distributed. The station remains in the active state until it has completed its transmission, and then it returns to the idle state. It will then become active again after an exponentially distributed time period.

Table 1: Parameters for the analysis and simulation of the IEEE 802.11 MAC protocol

Parameter Descriptions	Values
Physical layer parameters	FHSS standard (see [1,2])
Channel bit rate	1Mb/s
DCF access method	Basic, Four-way handshaking
Minimum backoff window	8
Maximum backoff window	256
Maximum payload in a data frame	8184 bits
Payload	8184, 4348, 2430, 512 bits
Other protocol parameters	(see [2])

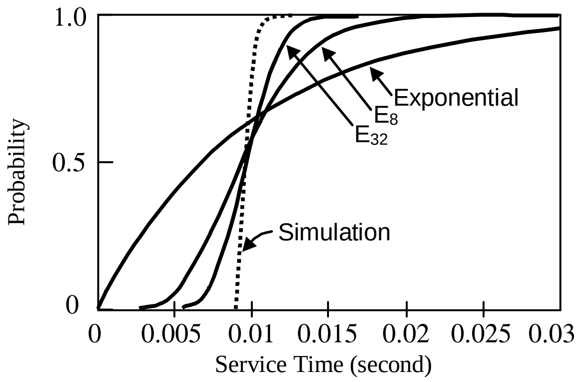

Figure 4: The CDFs of an exponential, Erlang random variables and the service time of the IEEE 802.11 MAC protocol for k=20 and payload=8184 bits

4.1 Delay Performance of IEEE 802.11 with the Four-way Handshaking Access Method

We first assume that each station, when ready for transmission, carries a fixed size data frame. To get the insight into the service time distribution which is not available in [2], we use simulation to obtain the Cumulative Distribution Function (CDF) of a typical service time distribution of IEEE 802.11, with the protocol parameters shown in Table 1. Here we consider the *Frequency Hopping Spread Spectrum* (FHSS) option in the physical layer. This CDF is described in Figure 4, and it is compared with the CDFs of exponential, Erlang with parameters 8 (E_8) and Erlang with parameter 32 (E_{32}) random variables, all of them with the same mean value. Notice that according to the results presented in Figure 4, the service time distribution is close to deterministic. This is mainly because of the fixed payload size. As the payload transmission time, which is fixed, accounts for as high as 80% of the total service time in average, the service time distribution is mainly dominated by the distribution of the payload size. This of course suggests that IEEE 802.11 is efficient.

As can be seen, clearly, the service time distribution under saturated traffic condition, namely, the distribution of the time between two successive successful data frame transmissions, of the IEEE 802.11 MAC protocol, is not exponentially distributed. Whereas, E_8 and E_{32} appear better to describe the service time distribution of the protocol. We therefore recommend using E_8 to model the IEEE 802.11 MAC protocol service time distribution.

To analyze IEEE 802.11 with 50 mobile stations, we construct a stated dependent CTMC-SSQs – the SD-M/E_8/1/50 system. The balance equations of the M/Ej/1/k system are given in the Appendix. Parameters used for the protocol are given in Table 1. The numerical results computed by Successive Over-

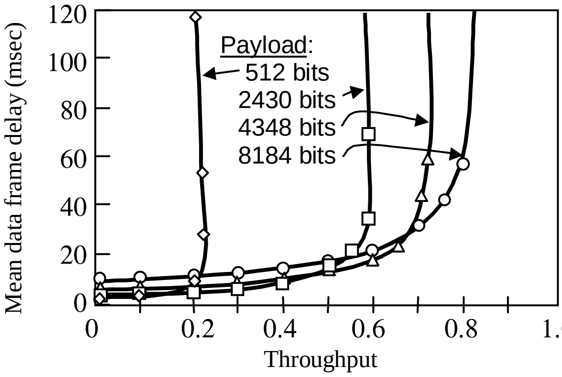

Figure 5: The delay performance of the IEEE 802.11 MAC protocol with the four-way handshaking access method

Relaxation (shown in solid lines) as well as the simulation results (shown in symbols) are compared in Figure 5.

The very close agreement between the numerical and simulation results presented in Figure 5 indicates the robustness of our approach and confirm the use of E_8 as the service time distribution of the IEEE 802.11 MAC protocol under fixed size data frame assumptions.

Furthermore, in Figure 5, the effect of the data frame size on the delay performance is demonstrated. The benefit of using a larger data frame is clearly presented as the protocol offers a higher achievable throughput level for a larger data frame size. This result is consistent with other analyses performed on similar protocols such as CSMA with Collision Detection (CSMA/CD) [7].

In the light traffic zone, for example the 15% throughput level, the mean transmission delay of a larger data frame is slightly higher than a smaller data frame, mainly due to the longer data frame transmission time requirement for the larger data frame. However, the difference in terms of the average transmission delay between the two different sizes under this traffic condition is insignificant.

4.2 Delay Performance of IEEE 802.11 with the Basic Access Method

Under the same assumptions made in the previous subsection, we evaluate the delay performance of the IEEE 802.11 MAC protocol with the basic access method. We again use the saturation throughput of the protocol with the basic access method of [2]. Having the saturation throughput results, we construct the SD-M/E_8/1/50 system for which the balance equations and all necessary parameter values are given in the Appendix.

The delay performance of IEEE 802.11 with the basic access method is presented in Figure 6. The numerical results are shown in solid lines and the simulation results are plotted in symbols. Figure 6 also compares the delay performance between the basic access method and the four-way handshaking access method that is shown in dotted lines.

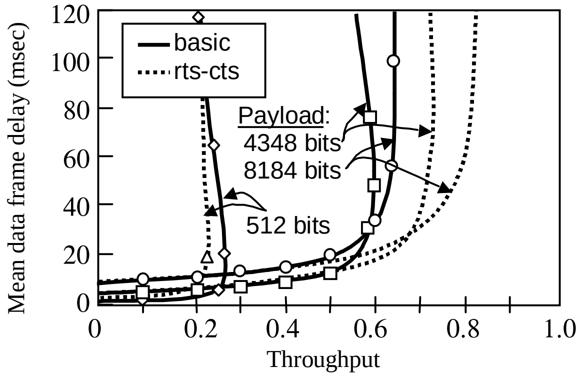

Figure 6: The delay performance of the IEEE 802.11 MAC protocol with the basic access method

In this analysis, three fixed data frame sizes are assumed, of which their payload sizes are 512, 4348 and 8184 bits. By comparing the delay performance for different data frame sizes with the basic access method, we notice a similar effect as in the four-way handshaking access method, where the larger data frame offers a higher achievable throughput level.

It is shown in Figure 6 that the difference in delay performance between the different access methods is significant. We see that the four-way handshaking access method offers a higher achievable throughput than the basic access method for the same data frame size. This is mainly due to the reason that in case of a collision, senders using the four-way handshaking access method detect the collision earlier than senders using the basic access method. Hence, the channel wastage due to collision for the four-way handshaking access method is much shorter than the basic access method.

Since senders using the four-way handshaking access method require an additional RTS/CTS exchange, the average delay for the four-way handshaking access method is expected to be higher than that for the basic access method in light traffic when collisions are not intensive. From the results shown in Figure 6, the four-way handshaking access method indeed produces slightly higher delay in average in some cases, however, the differences are only limited to a few milliseconds. The only case where the basic access method performs noticeably, but not significantly, better than the four-way handshaking access method is when the data frame size is very small, in our case, it is the data frame that carries 512 bits paylaod.

4.3 The Effect of Data Frame Distribution on the Delay Performance

To further investigate the effect of the data frame sizes on the delay performance, we now consider a dual fixed data frame size situation. This assumption is said to be more realistic than the one based on fixed data frame size [8], and it effectively increases the variance of the data frame size distribution. In particular, we consider two possible data frame payload sizes: 512

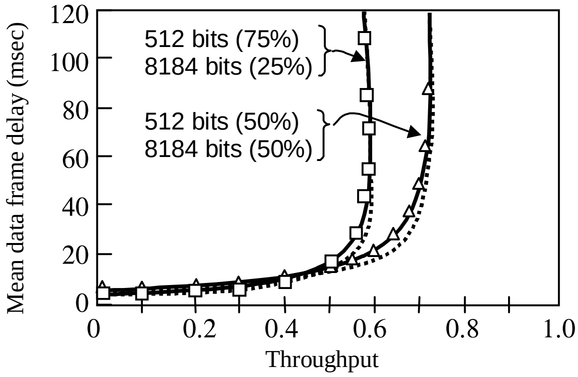

Figure 7: The delay performance of the IEEE 802.11 MAC protocol for dual fixed data frame size

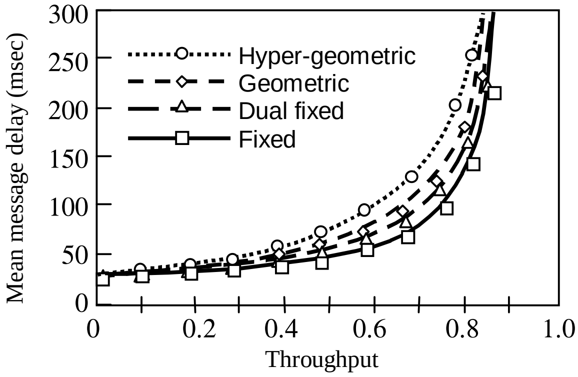

Figure 8: The delay performance of the IEEE 802.11 MAC protocol for trains of data frames

bits and 8184 bits. Two cases are assumed here. In the first, 75% of the frames are of 512-bit and 25% are of 8184-bit payload sizes. In the second case, half of the data frames are of 512-bit and the other half are of 8184-bit payload sizes.

Using the same approach, to model the dual data frame size distribution, we construct a state dependent M/PH/1/50 system of which the PH service process is a hyper-Erlangian process. The balance equations for this system are provided in the Appendix.

The delay performance of IEEE 802.11 with four-way handshaking access method, and under the dual data frame size assumption, is presented in Figure 7. The solid lines and symbols represent the numerical and simulation results respectively. Moreover, we include the numerical results taken from Figure 5 (shown in dotted lines) to compare the delay performance between fixed data frame size and dual fixed data frame size assumptions that have the same mean value.

As in Figure 7, an excellent agreement between the numerical and simulation results has again been achieved. This also indicates the robustness and versatility of the approach where the model is not limited to a certain data frame distribution. Our interest here is also the investigation of the effect of the data frame distribution on the delay performance. Surprisingly, the increase in variance in data frame distribution has only a little effect on the mean transmission delay. The average delay of the dual size data frame distribution appears to be just slightly higher than that of the fixed size data frame distribution.

Table 2: Various message size distributions used in Section 4.4

Distribution	Mean (bits)	Variance (bit^2)
Fixed	24576	0
Dual fixed 512 bits (36%) 38112 bits (64%)	24576	$(18048)^2$
Geometric	24576	$(24576)^2$
Hyper-geometric 512 bits (36%) 38112 bits (64%)	24576	$(35432.2)^2$

4.4 Performance Evaluation of IEEE 802.11 with Trains of Data Frames

This subsection studies the effect of train size distribution on average delay assuming that a station transmits a burst that contains a train of data frames when it becomes active. The inter-burst time period of a station, that is the time period from which the station becomes idle due to a successful transmission of a burst until a new burst is generated, is exponentially distributed. According to the IEEE 802.11 FHSS physical specification, the longest specified data frame carries a payload of 8184 bits [1]. To transmit a message longer than that, the fragmentation operation described in Section 2 is used.

To perform the analysis, we first notice that the fragmentation operation is not modeled in [2]. To include the fragmentation, for the four-way handshaking access method, the variable T_s^{rts} in [2], which is the time duration for a successful transmission, must be modified. The new successful transmission time duration, $T_s^{rts^*}$, must include the additional overhead due to the fragmentation depicted in Figure 2. It can be expressed by

$$T_s^{rts^*} = T_s^{rts} + \left\lceil \frac{\mathrm{E}[P]}{8184} - 1 \right\rceil \cdot \left(2SIFS + 2\delta + ACK + H\right) \quad (2)$$

where E[P] is the average size of the message expressed in bits, *SIFS* is the SIFS duration period, *ACK* is the ACK frame transmission time, δ is the signal propagation time, H is the header transmission time of a data frame, and $\lceil x \rceil$ represents the smallest integer value larger than x. Note that this modification also applicable to the basic access method.

With the appropriate modification, Equation (13) in [2] can now be used for delay performance analysis of IEEE 802.11 with the four-way handshaking access method assuming that a station may carry a long message that will generate a train of data frames. We consider four message size distributions (listed in increasing variance values): fixed, dual fixed, geometric and hyper-geometric. The statistical characteristics of these four message size distributions are presented in Table 2.

The performance analysis under the fixed and dual fixed message size assumptions can be performed using $M/E_8/1/50$ and M/PH/1/50 systems respectively. For the message size having geometrically distribution function, M/M/1/50 is used instead. This is because as we have learned in the previous subsections, the service time of IEEE 802.11 is highly dominated by the data frame transmission time, thus exponential service time, which is the continuous version of its geometric counterpart, is appropriate to model this case. For the case of hyper-geometric message size distribution, the M/PH/1/k system is used where the service process is a hyper-exponential service process.

The delay performance of the IEEE 802.11 MAC protocol under the four different message size distributions is demonstrated in Figure 8. Firstly, we notice from the figure the very good match between the numerical (shown in lines) and the simulation (shown in symbols) results. Secondly, as in the previous subsection, we notice that the message size distribution is insensitive to the mean delay performance of the IEEE 802.11 MAC protocol. A higher variance in message size distribution appears to result in only slightly longer transmission delay.

5. CONCLUSIONS

In this paper, we have provided the delay performance of the IEEE 802.11 MAC protocol under realistic assumptions without compromising the protocol details. To perform the analysis, we employ a new approach that is applicable to the IEEE 802.11 MAC protocol. Not only the approach retained all the protocol details, it also allows a more general arrival process to be included which leads to more accurate and realistic results. The excellent match between the numerical and simulation results demonstrated throughout this paper has confirmed the robustness of the approach.

From the numerical results, the efficiency of the IEEE 802.11 MAC protocol is again presented, especially the four-way handshaking access method. Even the four-way handshaking access method requires additional RTS/CTS frame exchange operation, the overhead of this operation is insignificant whereas its benefits are clear. Another result concluded from the numerical results is the insensitivity of the average transmission delay to message size distribution of the protocol.

APPENDIX

In this appendix, we provide the steady state balance equations for the M/Ej/1/k system and the M/PH/1/k system. Note that the M/M/1/k system is a special case of the M/Ej/1/k system by setting j=1.

A1. The M/Ej/1/k System

Recall that k is the number of mobile stations in an IEEE 802.11 network. Let p_n be the probability that a system will stay in state n, with $0 \le n \le k$. The mean arrival rate, $\bar{\lambda}$, of the system is

$$\bar{\lambda} = \sum_{n=0}^{k} \left(\lambda(n) \cdot p_i \right) \qquad \text{(A-1)}$$

and the throughput, ρ, is given by

$$\rho = \bar{\lambda} \cdot d_t \qquad \text{(A-2)}$$

where $\lambda(n)$ is the mean arrival rate of state n, and d_t is the mean transmission time of the payload in a data frame.

Since each station is statistical identical and it transmits a new data frame after an exponential random time provided that it has just completed a data frame transmission, the overall arrival rate of a particular state n can be expressed as

$$\lambda(n) = \lambda_{ind} \cdot (k-n), \quad n = 0,1,\ldots k \qquad \text{(A-3)}$$

where λ_{ind} is the arrival rate of a station. The steady state balance equations for the M/Ej/1/k system are

$$0 = -\lambda(0) p_0 + j\mu(1) p_{1,1},$$

$$0 = -(\lambda(1) + j\mu(1)) p_{1,j} + j\mu(2) p_{2,1} + \lambda(0) p_0,$$

$$0 = -(\lambda(1) + j\mu(1)) p_{1,i} + j\mu(1) p_{1,i+1}, \quad (i = 1,2,\ldots, j-1)$$

$$0 = -(\lambda(n) + j\mu(n)) p_{n,j} + j\mu(n+1) p_{n+1,1} + \lambda(n-1) p_{n-1,j}, \quad (n = 2,3,\ldots, k-1)$$

$$0 = -(\lambda(n) + j\mu(n)) p_{n,i} + j\mu(n) p_{n,i+1} + \lambda(n-1) p_{n-1,i}, \quad (n = 2,3,\ldots, k-1;\ i = 1,2,\ldots, j-1)$$

$$0 = -j\mu(k) p_{k,j} + \lambda(k-1) p_{k-1,j},$$

$$0 = -j\mu(k) p_{k,i} + j\mu(k) p_{k,i+1} + \lambda(k-1) p_{k-1,i}, \quad (i = 1,2,\ldots, j-1)$$

with

$$p_n = \sum_{i=1}^{j} p_{n,i}, \qquad (n = 1,2,\ldots,k)$$

$$\sum_{n=0}^{k} p_n = 1$$

where $j \cdot \mu(n)$ represents the service rate of state (n,i) for $n \ge 1$; p_0 is the probability that the system is in state 0, and $p_{n,i}$ is the probability that the system is in state (n,i).

The parameters used to generate Figure 5 are: j=8, k=50, d_t is equal to any of the 0.512, 2.430, 4.348, 8.184msec, $\mu(n)$ is obtained by Equations (13) and (17) in [2] and (1) with $1 \le n \le k$. The mean arrival rate and the throughput of the system can be computed by (A-1), (A-2) and (A-3) given a λ_{ind} value. The balance equations are solved by Successive Over-Relaxation, and finally the mean delay can be obtained by applying Little's formula [9].

The parameters used to produce Figure 6 are the same as that used to obtain Figure 5, except that $\mu(n)$ is obtained by equations (13) and (14) in [2] and (1) with $1 \le n \le k$ in this case.

In Figure 8, the results of fixed message size distribution is obtained by setting the parameter j=8, k=50, and d_t=24.576msec. Furthermore, $\mu(n)$ is obtained by Equation (13) in [2], (1) and (2) in this paper for $1 \le n \le k$.

The results of the geometric message size distribution in Figure 8 is computed similar to the previous one except that j=1.

A2. The M/PH/1/k System with Hyper-Erlangian Service Process

To facilitate the dual message size, we construct a M/PH/1/k system where the service process is a Hyper-Erlangian service process. Two service rates are required in this system, which are $\mu_b(n)$ where b=1,2. Moreover, we define α_b to be the probability that the service rate of a message is $\mu_b(n)$.

The balance equations for such a M/PH/1/k system are

$$0 = -\lambda(0)p_0 + j\mu_1(1)p_{1,1,1} + j\mu_2(1)p_{1,1,2},$$

$$0 = -(\lambda(1) + j\mu_b(1))p_{1,j,b} + \alpha_b\lambda(0)p_0 + \alpha_b j\mu_1(2)p_{2,1,1} + \alpha_b j\mu_2(2)p_{2,1,2}, \quad (b = 1,2)$$

$$0 = -(\lambda(1) + j\mu_b(1))p_{1,i,b} + j\mu_b(1)p_{1,i+1,b}, \quad (i = 1,2,\dots, j-1;\ b = 1,2)$$

$$0 = -(\lambda(n) + j\mu_b(n))p_{n,j,b} + \lambda(n-1)p_{n-1,j,b} + \alpha_b j\mu_1(n+1)p_{n+1,1,1} + \alpha_b j\mu_2(n+1)p_{n+1,1,2}, \quad (n = 2,3,\dots,k-1;\ b = 1,2)$$

$$0 = -(\lambda(n) + j\mu_b(n))p_{n,i,b} + \lambda(n-1)p_{n-1,i,b} + j\mu_b(n)p_{n,i+1,b}, \quad (n = 2,3,\dots,k-1;\ i = 1,2,\dots, j-1;\ b = 1,2)$$

$$0 = -j\mu_b(k)p_{k,j,b} + \lambda(k-1)p_{k-1,j,b}, \quad (b = 1,2)$$

$$0 = -j\mu_b(k)p_{k,i,b} + \lambda(k-1)p_{k-1,i,b} + j\mu_b(k)p_{k,i+1,b}, \quad (i = 1,2,\dots, j-1;\ b = 1,2)$$

with

$$p_n = \sum_{i=1}^{j}(p_{n,i,0} + p_{n,i,1}), \quad (n = 1,2,\dots,k)$$

$$\sum_{n=0}^{k} p_n = 1$$

where $j \cdot \mu_b(n)$ represents the service rate of state (n,i,b) for $n \ge 1$; p_0 is the probability that the system is in state 0, and $p_{n,i,b}$ is the probability that the system is in state (n,i,b).

The parameter used to produce the results of the dual fixed message size distribution presented in Figure 8 are: j=8, k=50, α_1=0.36, α_2=0.64, $\mu_1(n)$ and $\mu_2(n)$ are obtained by Equation (13) in [2], (1) and (2) for $1 \le n \le k$, with d_t=0.512 and 38.112msec respectively.

The parameters for generating the results of hyper-geometric message size distribution shown in Figure 8 are similar to the previous case except j=1.

Results shown in Figure 7 can be obtained by similar way with applying appropriate parameters.

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