# A new approach to service differentiation in wireless Ad Hoc networks

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This paper proposes a new modification to the IEEE 802.11 Distributed Coordination Function (DCF) Medium Access Control (MAC) protocol originally designed to support best-effort data services. We extend the DCF to provide service differentiation for delay sensitive, and best-effort traffic. An analytical model to compute the modified DCF delay, in the assumption of finite number of terminals is presented. The analytical model allows applications to tune their modified MAC parameters so as to achieve a given degree of service differentiation. Simulation results have shown a good agreement with the analytically predicted performance. It also showed that the modified MAC provides good service differentiation in terms of the expected delay over a reasonably wide range of high priority and best-effort traffic mixes.

يقدم هذا البحث تعديلا جديدا لبروتوكولات عمل شبكات المحمول آلتي لا تعتمد على محطات الربط. يهدف هذا التعديل إلى إعطاء هذه الشبكات القدرة على تبادل الرسائل المعلوماتية و كذلك المكالمات الصوتية مع ضمان جودة الأداء اللازمة لكل منهما. أظهرت نتائج البروتوكول المعدل قدرة جيدة على التحكم في جودة الأداء المطلوب تحقيقها و قد بات واضحا صلاحية البروتوكول المعدل للعمل مع البروتوكولات القياسية.

**Keywords:** Wireless ad hoc networks, Service differentiation, Modified MAC

## 1. Introduction

A key component in the development of single channel ad hoc network, is the Medium Access Control (MAC) protocol with which nodes share a common radio channel. Such a protocol has to provide an efficient use of the available bandwidth, while satisfying the quality of service requirements of both data, and real-time applications. It is envisioned that TCP/IP will be the glue for all applications in future mobile environments, many of them (e.g., real-time applications) requiring better than best-effort services [1]. This includes applications such as voice, and video which requires a strict quality of services in terms of delay variability and losses.

There are two principle approaches to support better than best-effort services for Internet-based services in a future wireless network. The first approach begins with the conventional circuit switched paradigm, and extends it with datagram services. These systems are characterized by strict control over both the wire and wireless resources in order to maintain good quality in the wireless environment [2,3]. The second approach is based on an important design principle that mandates that only minimal control, and signaling is viable, since due to the dynamic nature of the Ad Hoc networks. It is difficult to dynamically assign a central controller to maintain the diversity of applications in the Internet-based wireless applications. The Differentiated Services (DiffServ) concept of the Internet Engineering Task Force (IETF) [4], follows this principle. A good example for such a wireless technology, is the IEEE 802.11-DCF standard [5], which is compatible with the current best-effort service model of the Internet. The DCF mechanism of the IEEE 802.11, has been investigated in numerous papers. In [6, 17], a distributed solution for the support of real-time sources over IEEE 802.11 is discussed, which modifies the MAC to send short transmission to gain priority for real-time service. This approach is capable of offering bounded delay, however its disadvantage is that it has significant limitations for applications with variable data rates. The fairness of the distributed control is investigated in [8], and [9]. Both papers suggest distributed algorithms for rate-based Service Differentiation (ServDiff). Both papers solve the problem of throughput fairness. However, these contributions do not analyze the level of delay differentiation. Theoretical analysis of the DCF protocol can be found in [10], and the performance evaluation of the IEEE 802.11 has been carried out either by means of simulation [11], or by means of analytical models with constant or geometrically distributed backoff window in [12,13], and with exponential backoff window in [14]. In [15], [16], several wireless scheduling algorithms are analyzed. These algorithms, however, relies on centralized control, and polling of backlogged mobile hosts. In [17], the well known additive increase, multiplicative decrease (AIMD) mechanism of [17] is adapted to deliver ServDiff in ad hoc networks. Another example is in [18], where in the DCF algorithm is modified to support ServDiff by using different minimum contention windows for different priority traffic classes. The basic difficulty of this approach is that in the IEEE 802.11 standard, the backoff windows are hard wired in the physical layer details [4], thus they can not be made dependent on the network (traffic) state. As a consequence of this lack of flexibility, the throughput in some network scenarios can be significantly lower than the maximum achievable.

In this paper a modified MAC protocol that provides ServDiff at the DCF MAC interface is being proposed and analyzed, and validated. The proposed system is seen to be more flexible than that in [18], and more impotently, is that it does not violate the Physical/MAC layer standards, hence it is more suited to be implemented on top of the standard Physical/MAC.

This paper is outlined as follows, section 2, outlines the IEEE 802.11 DCF MAC protocol. Details of the modified MAC is presented in section3. In section 4, the packet arrival time randomization model is characterized, and its underlying assumptions are discussed. Analytical results of the modified MAC's model is demonstrated in section 5, and compared with that obtained via simulation in section 6. A summary for the findings presented in this paper is given in section 7 with some conclusions.

## 2. The IEEE 802.11-DCF MAC protocol

The IEEE 802.11-DCF MAC protocol is a carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol. In the DCF mode, a station must sense the medium before initiating the transmission of a packet. If the medium is sensed as being idle for a time interval greater than a Distributed Inter-Frame Space (DIFS), then the mobile station transmits the packet. Otherwise, transmission is differed, and a backoff process is entered. Specifically, the station computes a random value in the range of the so called Contention Window (CW). A backoff time interval is computed using this random value:

$$T_{backoff} = Rand(0, CW) \times T_{slot} ,$$

where $T_{slot}$, is the Hello by language of people in Hawii (ALOHA) time slot [4]. This backoff interval is then used to initiate a backoff timer. The timer is decreased only when the medium is idle, and is frozen when another station is detected as transmitting. Each time the medium becomes idle for a period longer than DIFS, the backoff timer is periodically decremented once every slot time. As soon as the backoff timer expires, the mobile station accesses the medium. A collision occurs when two or more mobile hosts start transmission simultaneously in the same slot. An acknowledgment is used to notify the sending station that the transmitted frame has been successfully received. If an acknowledgment is not received, the station assumes that the frame was not received successfully, and schedules a retransmission, reentering the backoff process. To reduce the probability of collision, after each successful transmission attempt, the CW is doubled until a predefined maximum ($CW_{max.}$) is reached.

After a successful or unsuccessful frame transmission, if the station still has frames queued for transmission, it must execute a new backoff process.

## 3. Modified IEEE 802.11-DCF MAC protocol

The basic 802.11-DCF standard is not capable of supporting better than best-effort TCP services. This section, proposes a modified MAC protocol that runs in the mobile station, ensures that delay sensitive applications are effectively differentiated in their services with respect to best-effort classes.

The modified MAC protocol consists of a number of mechanisms built on top of the IEEE 802.11-DCF MAC protocol. As illustrated in fig. 1, the packet classifier operates between the IP, and the DCF MAC layer. The classifier is capable of differentiating real-time, and best-effort packets. Two slotted ALOHA randomization mechanisms are employed such that: one with parameter $P_0$, and the other is with parameter $P_r$.

The goal of the slotted ALOHA is to randomize the time at which best-effort packets access the DCF MAC. The idea of time randomization suggests itself to create a random time before the best-effort packets access the (shared) DCF mechanism, hence, reducing the interference between the arrival times of both types of traffic which is known to improve the throughput of the multiaccess medium. As shown in fig. 1, while real-time packets access the DCF MAC immediately. A newly generated best-effort packet accesses the DCF MAC, at beginning of any CW, with probability $P_0$, (note that R in fig. 1 is a uniformly distributed random number in the 0 to 1 range). On the other hand, if collision is detected, then this (backlogged) packet schedules for retransmission (i.e. re-access) at beginning of any CW with probability $P_r$ until it is successfully transmitted. Of importance here to note that $P_0$ is devised to control the new best effort traffic, while $P_r$ is meant to control the expected number of backlogged stations. In the next section, we analyze the behavior of the slotted ALOHA system with the control parameters, $P_0$, and $P_r$.

## 4. Analysis of the slotted ALOHA mechanism

In previous section, the modified MAC protocol, and its operating procedures have been identified. Here, the slotted ALOHA model, and its underlying assumptions are presented.

Consider a slotted ALOHA channel with N-users comprising an Ad Hoc wireless network. Each user can be in either the originating mode or in a retransmission mode. A user in the originating mode will generate a new packet in any CW-time with probability $P_0$, while a previously collided (backlogged) packet will re-access the DCF MAC with probability $P_r$ in all CWs following the original one until it is sent. The state of such a slotted ALOHA system can be completely described by telling how many mobile stations are blocked. In state K, there are K packets backlogged. In this state, the expected number of backlogged packets per CW is K$P_r$, and the expected number of new packets is (N-K)$P_0$, per CW. This ALOHA system moves around among a finite number of discrete states at discrete time slots. Now, by adopting the memory less assumptions, and by defining the process $X(t)$, $t$=1, 2, 3,..., which describes the state variable of the ALOHA system. The process $X(t)$ which assumes one of $(N+1)$ possible values of $n$: {0, 1, 2,..., $N$}, can be modeled as a finite state Markov chain with $P_{i,j} = P\left[x(t+1) = j \middle| x(t) = i\right]$ as its state transition probabilities. Where $P_{i,j}$ denotes the probability of the system being in state $i$, moving to state j. In order to identify the transition probabilities, let n represents the total number of new packets generated by ($N$-$i$) unblocked stations during the current CW, with $0 \le n \le N-i$. Similarly, let $r$ represents the number of retransmission's attempted by the i backlogged stations during the same CW with $0 \le r \le i$. With these notations, the transition probabilities can be written as follows:

$$\begin{aligned}
P_{i,j} &= 0, \qquad j \le i-2, \\
P_{i,i-1} &= P(n=0)P(r=1), \\
P_{i,i} &= P(n=0)P(r \ne 1) + P(n=1)P(r=0), \\
P_{i,i+1} &= P(n=1)P(r \ge 1), \\
P_{i,j} &= P(n=j-i), \; j \ge i+2, \qquad (1)
\end{aligned}$$

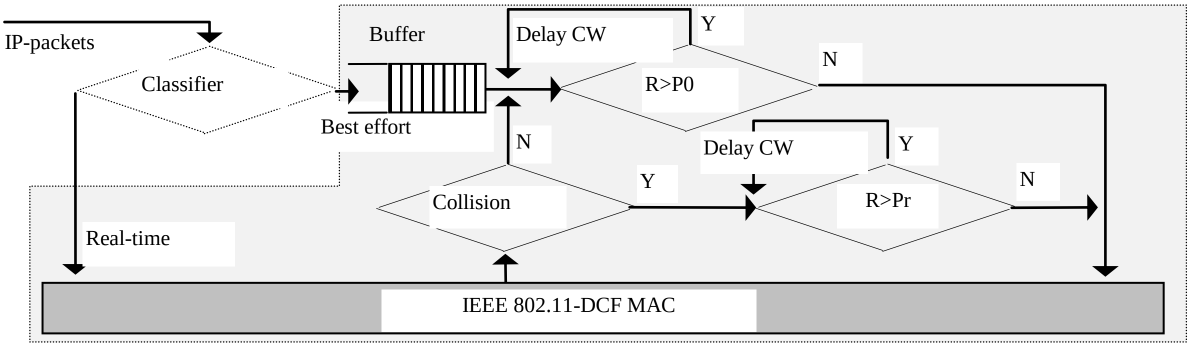

Fig. 1. Modified MAC.

with

$$\begin{aligned}
&P(n=0) &&= (1-P_0)^{N-i},\\
&P(n=1) &&= (N-i)P_0(1-P_0)^{N-i-1},\\
&P(n=j-i) &&= \binom{N-i}{j-i}P_0^{\,j-i}(1-P_0)^{N-j},\\
&P(r=0) &&= (1-P_r)^{i},\\
&P(r=1) &&= iP_r(1-P_r)^{i-1},\\
&P(r\neq 1) &&= 1-iP_r(1-P_r)^{i-1},\\
&P(r\geq 1) &&= 1-(1-P_r)^{i},
\end{aligned} \tag{2}$$

substituting eq. (2) into eq. (1) gives the state transition probabilities as follows:

$$P_{i,j}=\begin{cases}
0, & j\leq i-2\\
(1-P_0)^{N-i}iP_r\times\;(1-P_r)^{i-1}, & j=i-1\\
(1-P_0)^{N-i}[1-iP_r(1-P_r)^{i-1}] & \\
\quad+(N-i)P_0(1-P_0)^{N-i-1}\times(1-P_r)^{i}, & j=i\\
(N-i)P_0(1-P_0)^{N-i-1}\times[1-(1-P_r)^{i}], & j=n+1\\
\binom{N-i}{j-i}P_0^{\,j-i}\times(1-P_0)^{N-j}, & j\geq i+2,
\end{cases} \tag{3}$$

the expected packet flow $f(i)$ at state $i$, is, therefore, given by

$$\begin{aligned}
f(i) &= P(n=1)P(r=0)+P(n=0)P(r=1)\\
&= (1-P_0)^{N-i-1}(1-P_r)^{i-1}\times\\
&\quad [(N-i)P_0(1-P_r)+iP_r(1-P_0)].
\end{aligned} \tag{4}$$

In order to find the expected packet flow $S$, at DCF input, we need to find the equilibrium probabilities, $\pi_k,\;\; k=0.,1,2,\ldots,N$, of finding the system in state $k$. This is carried out by solving the following simultaneous linear equations:

$$\pi_j=\sum_{i=0}^{N}\pi_i P_{i,j},\quad j=0,1,2,\ldots,N,$$

subject to the constraint,

$$\sum_{i=0}^{N}\pi_i=1.$$

Therefore, $S$ is given by,

$$S=\sum_{i=0}^{N}\pi_i f(i). \tag{5}$$

Now using Little's rule [7], we can find the mean packet delay in the slotted ALOHA mechanism:

$$D_{ALH}=\sum_{i=0}^{N} i\,\pi_i \Big/ \sum_{i=0}^{N}\pi_i f(i), \tag{6}$$

where $\sum_{i=0}^{N} i\,\pi_i$, is the mean number of back-logged stations. The overall delay of the Best-Effort (BE) packets in the modified MAC can, then, be approximated as follows:

$$D_{BE} = D_{ALH} + D_{DCF}\,, \tag{7}$$

where $D_{DCF}$, denotes the mean delay in the DCF MAC mechanism (e.g., fig. 1). The following formulas for $D_{DCF}$ can be found in [18], and is outlined in the Appendix,

$$D_{DCF} = \sigma\, d + (1 - \sigma)\, m, \tag{8}$$

where $\sigma$ denotes the channel utilization, and $d$ is given by,

$$d \cong 2^{u}\, T_{slot}\, (L\lambda + 1) \times \left( \frac{1 - (2P)^{\upsilon+1}}{1 - 2P} + 2^{\upsilon}\, \frac{P^{\upsilon+1}}{1 - P} \right), \tag{9}$$

where $\lambda$ is the mean arrival rate of best-effort packets, $L$ is mean packet transmission time, $T_{slot}$ is mini-time slot size, equal to normalized propagation delay, $P$ denotes the collision probability $= \lambda\, T_{slot}$, and

$$\sigma = \frac{L}{L + \frac{1}{\lambda}}\,,$$

$$u = W_{min.} - 1,$$

$$\upsilon = W_{max.} - W_{min.}\,,$$

and the contention window ranges from $2^{W_{min.}}$ to $2^{W_{max.}}$.

In the following section we use the analysis presents here to address the issue of how the slotted ALOHA mechanism will affect the mean delay of the best-effort packets for different levels of service differentiation.

## 5. Supporting the service differentiation using the modified MAC protocol

From the analysis developed in previous section, it is seen that *f(i)*, given by eq. (4), plays a central role in determining the expected throughput, *S*, and delay, $D_{BE}$, of the slotted ALOHA system. Specifically, by setting different values for the parameters, $P_0$, $P_r$, different levels of service can be achieved. Clearly, in real system, we must choose $P_r > P_0$, in order to guarantee stability of the ALOHA system. The goal of this section is to demonstrate the manner in which the parameters $P_0$, $P_r$, control the expected quality of service in terms of the throughput, and delay of the best-effort traffic. A typical plot of S, (i.e., eq. (5)), as function of $P_0$, at different values for $P_r$, is shown in fig. 2. Consider for example, the case of *N*=20 mobile stations comprising an *Ad* Hoc network. As can be seen, there is an almost, linear relationship between the expected throughput, and $P_0$, at different values of $P_r$ (before saturation). Recall that $P_0$, implies the mean new best-effort packet per CW. A similar behavior can be seen for networks of different sizes (e.g., *N*=50, 100 station). Next, fig. 3 shows the expected delay eq. (6), that corresponds to the previously obtained throughput profiles of fig. 2. Once again, the delay is, almost, linearly proportional to $P_0$ at different values of $P_r$, and for networks with different sizes (N=50, 100 stations). Now, it is due time to make the following observations:

- Each mobile host can choose the degree of service differentiation to be achieved by adjusting its modified-MAC parameters, $P_0$, $P_r$ independently of other mobile stations.
- From the analytical properties of the slotted ALOHA, we knew that its maximum achievable throughput is upper bounded by 37 percent (i. e., $e^{-1}$), which means that the rest of 63 percent of the DCF MAC capacity is guaranteed to the high priority (real-time), traffic. However, as far as the delay performance is concerned. We are able to achieve service differentiation even among the best-effort applications themselves (by assigning different $P_0$, $P_r$, for each individual best-effort application independently), in addition to the 37 percent service differentiation which is inherited in our system between the real, and non-real time applications.

Fig. 4, is included to complete our discussion. It shows the average DCF MAC delay eq. (8), as function of the best-effort traffic in terms of $P_0$. This result is obtained at fixed CW=16 (above the minimum of 8 as stated by the standard [4]), packet length of 850 byte, and 2 Mb/Sec. channel rate. As expected, the parameters $P_0$, $P_r$, control the input (best effort) traffic before actually accessing the DCF MAC mechanism eq. (5).

## 6. Simulation results of the modified MAC

In order to validate the operation of the modified MAC, a simulation model for the CSMA/CA Ad Hoc wireless network is developed. The model utilizes the slotted ALOHA mechanism on top of a typical DCF MAC as previously described in fig. 1. In the simulation model, each mobile host generates a delay sensitive, voice, traffic, and best-effort TCP traffic. Voice traffic is modeled using ON/OFF sources with exponentially distributed talk spurts, and OFF periods of 300 m Sec. average length. Traffic was generated during the ON periods at a rate of 32 K b/Sec., 850 byte packet length.

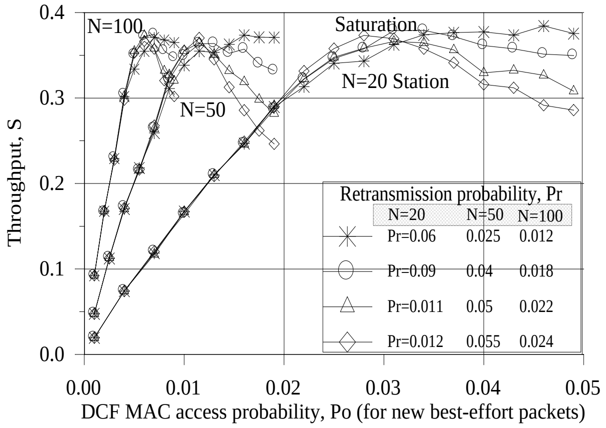

Fig. 2. Effect of control parameters, *Po* and *Pr* on the expected throughput of best-effort traffic: at the input of DCF MAC.

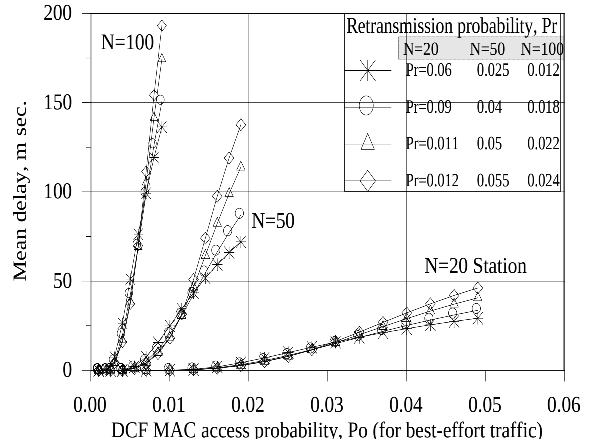

Fig. 3. Effect of the control parameters, *Po* and *Pr*, on the expected delay of the best-effort packets: at input of DCF MAC.

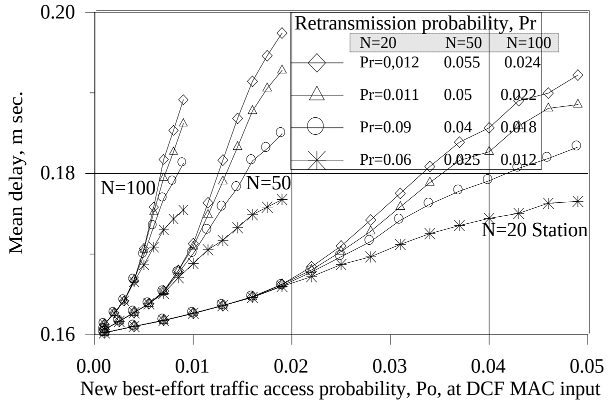

Fig. 4. Effect of the control parameters, *Po*, and *Pr*, on the expected delay of the best-effort traffic: due to typical DCF MAC mechanism.

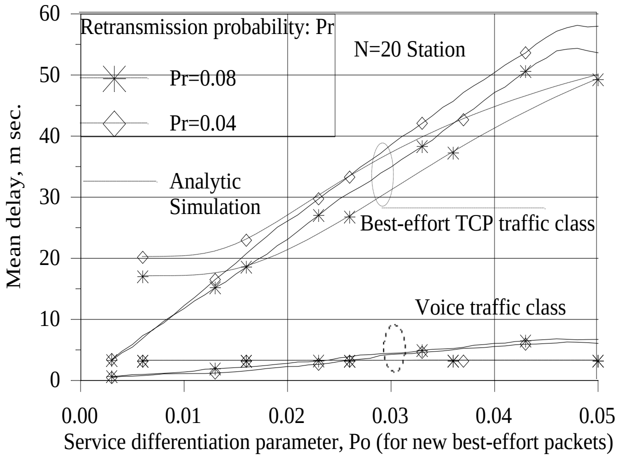

Fig. 5. Effect of control parameters, *Po*, and *Pr*, on the expected delay in the modified MAC protocol.

A set of simulation tests for Ad Hoc networks of different sizes (*N*=20, 50, and 100 station) are conducted. In all network scenarios, the channel rate is 2 Mb/Sec., CW=16 (above the standard minimum of 8).

Fig. 5, shows the expected delay versus the parameter $P_0$, at different values of $P_r$, in an *N*=20 station ad hoc network model. The analytical results (dash lines) are included for reference eq. (7) for best-effort, eq. (8) for voice). As can be seen, the simulation results show a reasonable agreement with the analytical ones, and the best-effort delay is, almost, linearly proportional to the value of

$P_0$. Moreover, the rate at which the delay of the voice packets increases, is significantly smaller than that for the best-effort packets. This indicates that the modified MAC enables the best-effort traffic to efficiently utilizes the free capacity leftover by the voice traffic over a relatively wide range of $P_0$. This is true because of the randomization mechanisms which have been incorporated in our system. The same observations made above, apply well for the larger sized network cases as can be seen in fig. 6, and fig.7. More importantly, form the (almost) linear relationship between the expected delay, and $P_0$. It is now clear that the modified MAC can efficiently enables each individual mobile host to pre-adjust the degree of service differentiation to be maintained among its applications independently of other hosts, and without violating the standard (Physical/MAC layers) window sizes of the IEEE 802.11 protocol.

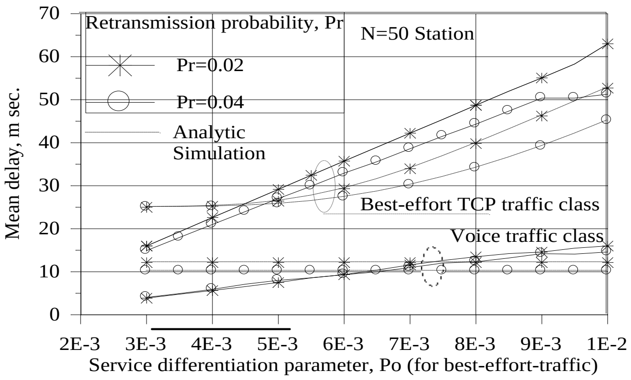

Fig. 6. Effect of the control parameters, *Po*, and *Pr*, on the expected delay in the modified MAC protocol.

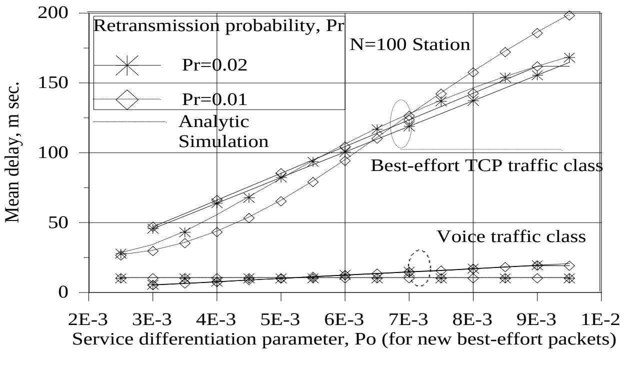

Fig. 7. Effect of the control parameters, *Po*, and *Pr*, on the expected delay in the modified MAC protocol.

## 7. Summary and conclusions

In this paper, a simple but effective modification to the DCF MAC protocol that can support real-time applications in mobile Ad Hoc wireless networks is presented, analyzed, and validated. Service differentiation is achieved by incorporating a slotted ALOHA-based packet arrival-time randomization mechanism with two control parameters. The randomization mechanism operates on top of the typical IEEE 802.11-DCF MAC protocol. An attractive feature of the proposed approach is that the randomization mechanism works independent of the underlying DCF MAC which makes it more suitable for practical implementation on top of the standard Physical/MAC layers. A simple analytical model is developed for the packet-time randomization system. A simulation model for Ad Hoc wireless network incorporating the modified MAC is developed. Simulation results have shown a reasonable agreement with the analytical ones over networks with different sizes. An attractive point for further research is to enable applications to tune the modified MAC parameters to match dynamic characteristics of the radio channel in an efficient manner. This we propose for future investigations.

## Appendix

In DCF MAC case, the average delay time conditional on the backoff procedure is approximated as:

$$d_i^{'} = \begin{cases} L^{'} + k_i L + b_i & for\ i = 1 \\ k_i L + b_i + L & for\ i > 1 \end{cases} , \qquad \text{(A-1)}$$

where $k_i$, denotes the number of packets sent during a given backoff period, $L$ is the packet transmission time, $L^{©}$ is the residual packet length, and, $b_i$ is a uniformly distributed deferred time in the range $[0,\ CW_i]$. Therefore, the total accumulated deferred time is estimated as:

$$d^{'} = \sum_{i=1}^{\infty} E\left[ \sum_{j=1}^{i} d_j^{'} \,\middle|\, i\ backoffs \right] \times (1 - P)P^{i-1} . \qquad \text{(A-2)}$$

The average backoff time is

$$E[b_j] = \begin{cases} T_{slot}\, 2^{W_{min}+j-2}, for, 1 \le j \le W_{\max} - W_{min} + 1 \\ T_{slot}\, 2^{W_{max}-1}, for, j \ge W_{\max} - W_{min} + 1 \end{cases}$$

and the average number of packets sent is

$$E[k_j] = \lambda E[b_j] \; . \tag{A-3}$$

Now by denoting $u=W_{min-1}$, and $v=W_{max}-W_{min}$, and substituting eqs. (A-2)-(A-3) into (A-1), the closed formula of eq. (9) is obtained.

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