Service Differentiation in Wireless LANs based on Capture

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***Abstract*— We investigate the effects of using a dual transmission power scheme for quality-of-service (QoS) differentiation in IEEE 802.11 wireless LANs. By setting hosts to transmit at different power levels, we enhance the likelihood that a high-power frame gets received correctly when a collision involving frames from both power levels occurs due to the *capture effect*. We develop a Markov model for the IEEE 802.11 DCF in a dual transmission power system over a Rayleigh-fading channel, and use it to evaluate the resulting performance, in terms of the key metrics of throughput and delay. Specifically, we study how the performance of the service classes depends on the proportion of hosts from each service class and the transmission power ratio, and demonstrate that, counter-intuitively, this dependence may be non-monotonic.**

I. Introduction

In contention-based access networks, such as ALOHA [1] and its various derivatives, hosts contend for a chance to transmit on the channel. When two or more transmissions overlap in time and space, a collision occurs, resulting in the mutual destruction of all frames involved. In wireless systems, however, it is sometimes possible for one of the colliding frames to be received correctly, provided that its received signal strength is sufficiently higher than that of the interferers; this is the so-called *capture effect* [2], [3].

The capture effect has been widely studied in the literature. Capture models for ALOHA were analysed in [4], [5], while the impact of multiple interferers on capture probability is the subject of [6]. The case for improving system throughput of an ALOHA network by using random transmission powers was argued in [7]. However, all of the above studies were performed in the context of generic ALOHA-like schemes. Works that have focused on wireless LAN MAC protocols, e.g. [8], [9] assume that all hosts transmit at the same power level, and hence capture occurs "inadvertently" due to fading and the near-far effect.

In this paper, we set out to study the performance of the IEEE 802.11's Distributed Coordination Fucntion (DCF) protocol when capture is introduced *deliberately* for the purpose of service differentiation, by using a dual transmission power scheme. Differentiation occurs because, in the event of a collision involving frames from both power levels, a high-power frame is more likely to be received at a level that is sufficiently above that of the interference, and, hence, be decoded correctly by the receiver. We study the extent of service quality differentiation (in terms of throughput and delay) made possible by using different transmission powers. We emphasise that this technique is easy to implement, as it requires no modifications to the IEEE 802.11 standard, which already supports transmission power level control (with the exact limits on the allowed power levels varying by country, due to regulation).

Our contribution is twofold; we first develop a Markov model for a dual transmission power system and then demonstrate the feasibility of capture based service differentiation in such a system. Our results show that a host always improves its own performance by switching from low to high transmission power. In addition we also observe several effects that are counterintuitive, e.g. the average delay of the low-power class is not monotonic in the number of high-power hosts. Finally, we show that significant differentiation is achievable even for low power ratios.

The rest of this paper is organised as follows. Section II presents the Markov model of the dual transmission power system and derives the key expressions used for the performance evaluation. Section III analyses the actual throughput and delay performance, taking into account the specific characteristics of the IEEE 802.11b standard while Section IV concludes the paper and outlines directions for further research.

II. The Dual Transmission Power Model

There has been considerable interest in modelling the performance of the IEEE 802.11 Distributed Coordination Function (DCF). In this paper, we build upon a widely accepted and referenced Markov model developed in [10], and extended in [11]. The Markov model of [10] was used to analyse the saturation throughput of DCF. In [11], the model was extended to account for the channel-busy probability, i.e. the probability that a host freezes its timer when it detects a busy medium; in addition, the extended model is then used to analyse both throughput and delay.

For brevity, we do not repeat the considerations behind the Markov chain model that forms the basis of this work, referring the reader instead to [10] and [11] for a detailed

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discussion. We however note that [11] includes in the Markov chain an additional state, the so-called $(-1, 0)$, to allow for a host sending consecutive frames without generating a back-off timer; this state appears inconsistent with the IEEE 802.11 standard and is therefore omitted in our subsequent analysis.

The Markov model is designed to reflect an infrastructure-based IEEE 802.11 wireless LAN under ideal channel conditions, i.e. without random bit errors or hidden terminals. We maintain the saturation assumption introduced in [10], namely, that all hosts have a nonempty transmission queue at all times. Due to symmetry considerations, it follows that, in the steady state, all hosts from the same class experience identical collision and channel-busy probabilities at each transmission attempt.

We now proceed to analyse the dual power model. Denote the collision and channel-busy probabilities, respectively, by p_H and b_H for the high-power hosts and by p_L and b_L for the low-power ones. Let $s(t)$ be the back-off stage for a host at time t. $s(t)$ takes values between 0 and m, where m is the maximum back-off stage. Let $b^H(t)$ and $b^L(t)$ be the back-off counters for high-power and low-power hosts, respectively. $b^H(t)$ and $b^L(t)$ take values between 0 and $2^i \cdot W - 1$, where i is the back-off stage and W is the minimum back-off window. Let $b^H_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b^H(t) = k\}$ and $b^L_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b^L(t) = k\}$ be the stationary probability distributions of the high-power and low-power Markov chains, respectively. Under steady state conditions, the following equations hold:

$$b^H_{i,0} = p_H^i b_{0,0} \qquad 0 \le i \le m-1 \tag{1}$$

$$b^L_{i,0} = p_L^i b_{0,0} \qquad 0 \le i \le m-1 \tag{2}$$

$$b^H_{m,0} = \frac{p_H^m}{1-p_H} b_{0,0} \tag{3}$$

$$b^L_{m,0} = \frac{p_L^m}{1-p_L} b_{0,0} \tag{4}$$

$$b^H_{i,k} = \frac{W_i - k}{W_i} \cdot \frac{1}{1-b_H} b_{i,0} \qquad 0 \le i \le m, 0 < k \le W_i - 1 \tag{5}$$

$$b^L_{i,k} = \frac{W_i - k}{W_i} \cdot \frac{1}{1-b_L} b_{i,0} \qquad 0 \le i \le m, 0 < k \le W_i - 1 \tag{6}$$

From the above expressions and the normalisation condition, it can be verified that the probability of a high-power (or low-power) host to be in the state $(0, 0)$ of its respective Markov chain is given, respectively, by

$$b^H_{0,0} = \frac{2(1-2p_H)(1-p_H)(1-b_H)}{W(1-p_H-(2p_H)^m + (1-2p_H)(1-2b_H)} \tag{7}$$

$$b^L_{0,0} = \frac{2(1-2p_L)(1-p_L)(1-b_L)}{W(1-p_L-(2p_L)^m + (1-2p_L)(1-2b_L)} \tag{8}$$

Thus, the probability τ_H that a high-power host transmits in a randomly chosen slot can be expressed as

$$\tau_H = \sum_{i=0}^{m} b_{i,0} = \frac{b^H_{0,0}}{1-p_H} = \frac{2(1-2p_H)(1-b_H)}{W(1-p_H-p_H(2p_H)^m) + (1-2p_H)(1-2b_H)}; \tag{9}$$

similarly, the probability τ_L that a low-power host transmits in a randomly chosen slot is given by

$$\tau_L = \sum_{i=0}^{m} b_{i,0} = \frac{b^L_{0,0}}{1-p_L} = \frac{2(1-2p_L)(1-b_L)}{W(1-p_L-p_L(2p_L)^m) + (1-2p_L)(1-2b_L)} \tag{10}$$

For a transmitting host, the probability of collision depends on two factors: the number of other frames, both high-power and low-power, transmitted in contention in the same slot (which we denote by n_H and n_L, respectively), and the probability of capture, denoted by $c_H(n_H, n_L)$ if the transmitted frame is a high-power one and $c_L(n_H, n_L)$ if it is low-power. The capture probability depends only on the physical characteristics of the channel and receiver, and not on the transmitting host's state in the MAC protocol.

Let the total number of high-power and low-power hosts in the wireless LAN be denoted by h and l, respectively. Then, the overall collision probability for a given high-power host is

$$p_H = \sum_{n_H=0}^{h-1} \sum_{n_L=0}^{l} \binom{h-1}{n_H} \tau_H^{n_H} (1-\tau_H)^{h-(n_H+1)} \cdot \binom{l}{n_L} \tau_L^{n_L} (1-\tau_L)^{l-n_L} \cdot [1 - c_H(n_H, n_L)], \tag{11}$$

and, similarly, the collision probability for a host transmitting at low power is

$$p_L = \sum_{n_L=0}^{l-1} \sum_{n_H=0}^{h} \binom{l-1}{n_L} \tau_L^{n_L} (1-\tau_L)^{l-(n_L+1)} \cdot \binom{h}{n_H} \tau_H^{n_H} (1-\tau_H)^{h-n_H} \cdot [1 - c_L(n_H, n_L)]. \tag{12}$$

Finally, the channel is detected busy by a host if any of the remaining $h + l - 1$ hosts is active in that slot. Thus, the probability of finding a busy channel in a randomly selected slot (for a high-power and a low-power host, respectively) is given by

$$b_H = 1 - (1-\tau_H)^{h-1}(1-\tau_L)^l \tag{13}$$

$$b_L = 1 - (1-\tau_H)^h(1-\tau_L)^{l-1} \tag{14}$$

We emphasise that the probability of a busy channel is affected by transmissions from either class equally: any host (regardless of its own transmission power) is obliged to freeze its counter during the back-off phase whenever it senses a carrier signal on the channel.

Expressions (9)-(14) form a system of equations in the unknowns τ_H, τ_L, p_H, p_L, b_H, and b_L, where W,m,h,l are fixed parameters, and $c_H(n_H,n_L)$,$c_L(n_H,n_L)$ are derived from the particular model used for the capture effect (which is independent of the IEEE 802.11 DCF model). These equations can be solved simultaneously to obtain the key parameters of the system.

For our numerical study we use a popular capture model that is derived from an assumption of independent and identically distributed Rayleigh fading channels between all transmitters and a central receiver (see, e.g., [7], [12]). In such channels, the received power at the destination host is given by $P_r = R^2 P_t$, where P_t is the transmission power and R is a Rayleigh distributed random variable. Consequently, the probability that a particular host (say, host 0), with a transmission power of $P_{t,0}$, captures the channel in the event of n simultaneous transmissions by other hosts, is given by

$$Pr\left[P_{r,0} \geq z_0 \cdot \sum_{i=1}^{n} P_{r,i}\right] = Pr\left[R^2 \geq z_0 \cdot \sum_{i=1}^{n} \frac{R^2 P_{t,i}}{P_{t,0}}\right],$$

which simplifies to (see [7])

$$Pr\left[P_{r,0} \geq z_0 \cdot \sum_{i=1}^{n} P_{r,i}\right] = \prod_{i=1}^{n} \frac{1}{1+\frac{z_0 P_{t,i}}{P_{t,0}}} \qquad (15)$$

where $P_{t,i}$ is the transmission power of host i, and z_0 is the capture threshold ratio. For the dual transmission power scenario, which is the subject of our study, with n_H interfering hosts transmitting at a power of $P_{t,H}$ and n_L additional ones transmitting at $P_{t,L}$, we get

$$c_H(n_H,n_L) = \left(\frac{1}{1+z_0}\right)^{n_H} \left(\frac{1}{1+\frac{z_0 P_{t,L}}{P_{t,H}}}\right)^{n_L} \qquad (16)$$

$$c_L(n_H,n_L) = \left(\frac{1}{1+z_0}\right)^{n_L} \left(\frac{1}{1+\frac{z_0 P_{t,H}}{P_{t,L}}}\right)^{n_H} \qquad (17)$$

In particular, we focus on the limit case, where the ratio between the transmission powers of the two classes is very high. In this case we use $P_{t,H} = 1000mW$ and $P_{t,L} = 1mW$ corresponding to the upper and lower limit transmission powers as specified in the standard and thus representing the maximum differentiation possible in a practical dual-power system. z_0 is set to 10dB.

III. Throughput and Delay Performance

A. Throughput

We now proceed to analyse the throughput performance of the dual-power wireless LAN. We focus on the IEEE 802.11b 'flavour' assuming model parameters as given in Table I, which reflect a typical IEEE 802.11b setting. In particular, we assume that all data frames are of equal size and that the size of transmission and control frames, and thus their transmission time, is negligible.

Due to the saturation assumption, all frames can be considered statistically identical and independent, thus the aggregate throughput of each power class is simply the expected number of successful bits from that class transmitted in a slot, divided by the average slot duration. This leads to the following expression for the aggregate throughput of the high-power hosts:

TABLE I
Model parameters.

Channel bit rate (C)	11Mbps
Physical Header (PH)	96μs
Empty slot time (emp)	20μs
MAC Header + FCS (MAC)	224 bits
Acknowledgement (ACK)	112 bits
Short Inter-Frame Space ($SIFS$)	10μs
DCF Inter-Frame Space ($DIFS$)	50μs
Frame Payload (P)	8184 bits
ACK Time-out ($ACKt$)	120μs
Minimum contention window (W)	32
Number of back-off stages (m)	5

$$S_H = (s_H \cdot t_H \cdot P)/[(1-t_H)(1-t_L)\cdot emp + (s_H \cdot t_H + s_L \cdot t_L)\cdot suc + (t_H(1-s_H) + (1-t_H)t_L(1-s_L))\cdot col], \quad (18)$$

where P and emp are the payload and duration of an empty slot respectively as given in Table I, while

- suc is the duration of a slot containing a successful frame and its acknowledgement, $suc = DIFS + SIFS + 2 \cdot PH + (MAC + P + ACK)/C$;
- col is the duration of a slot in which a collision occurs, $col = DIFS + PH + (MAC + P)/C$.

The aggregate throughput of the low-power hosts is given by

$$S_L = (s_L \cdot t_L \cdot P)/[(1-t_H)(1-t_L)\cdot emp + (s_H \cdot t_H + s_L \cdot t_L)\cdot suc + (t_H(1-s_H) + (1-t_H)t_L(1-s_L))\cdot col]. \quad (19)$$

Figure 1 plots the average throughput of each individual host for each power class. It is surprising to find that the throughput of a low-power host does not monotonically decrease with h; indeed, there exists a certain value of h for which the average low-power host throughput is minimal, and from that point, if more low-power hosts are 'converted' to become high-power, the throughput of the remaining low-power hosts increases (which, arguably, is counterintuitive). This can be

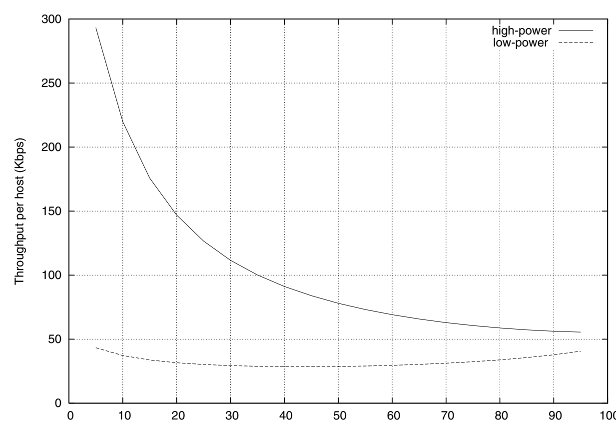

Fig. 1. Average per-host throughput in each power class.

explained by the fact that increasing the number of high-power hosts impacts first and foremost the performance of the other high-power; as the high-power collision probability rises, this causes more slots to become empty and available for successful low-power transmissions.

B. Delay

We now consider the MAC delay experienced by a frame transmitted on the channel. This delay consists of several components:

- the initial backoff before the frame is transmitted for the first time;
- for every time the frame is involved in a collision, its transmission time, followed by the acknowledgement timeout and another backoff period;
- the duration of the final, successful transmission, followed by the time until the acknowledgement is received.

We begin the calculation of the average delay by considering the expected total number of backoff slots during the 'lifetime' of a frame. The number of backoff slots before the frame is transmitted for the first time is uniformly distributed between 0 and $W-1$, as it immediately follows a successful transmission of a previous frame; thus, its expected number is $\frac{W-1}{2}$. After each subsequent collision, the number of backoff slots is distributed uniformly between 0 and $2^i \cdot W - 1$ with $i < m$ collisions so far, or between 0 and $2^m \cdot W - 1$ thereafter. Accordingly, since the probability of a high-power frame to be involved in a collision is p_H, the expected total number of backoff slots for a high-power frame is

$$X_H = \sum_{i=0}^{m-1} (p_H)^i \cdot \frac{2^i \cdot W - 1}{2} + \sum_{i=m}^{\infty} (p_H)^i \cdot \frac{2^m \cdot W - 1}{2} = \frac{1 - p_H - p_H \cdot (2p_H)^m}{2(1-2p_H)(1-p_H)} \cdot W - \frac{1}{2(1-p_H)}, \quad (20)$$

with p_H given by (11). Similarly, for a low-power frame,

$$X_L = \frac{1 - p_L - p_L \cdot (2p_L)^m}{2(1-2p_L)(1-p_L)} \cdot W - \frac{1}{2(1-p_L)}, \quad (21)$$

with p_L given by (12).

In the backoff counter is frozen whenever the slot is not empty, i.e. when a transmission by another host is sensed on the channel. Since, an arbitrary slot has a probability of $(s_H \cdot t_H + s_L \cdot t_L)$ to carry a successful frame and a probability of $(t_H(1-s_H) + (1-t_H)t_L(1-s_L))$ to contain a collision, we conclude that, on top of the X_H or X_L empty slots, the total backoff wait is extended, on average, by a further duration of

$$F_H = X_H[(s_H \cdot t_H + s_L \cdot t_L) \cdot suc + (t_H(1-s_H) + (1-t_H)t_L(1-s_L)) \cdot col]/[(1-t_H)(1-t_L)] \quad (22)$$

and

$$F_L = X_L[(s_H \cdot t_H + s_L \cdot t_L) \cdot suc + (t_H(1-s_H) + (1-t_H)t_L(1-s_L)) \cdot col]/[(1-t_H)(1-t_L)] \quad (23)$$

for high-power and low-power hosts, respectively, where suc and col are as defined in the previous subsection.

Finally, one has to add the duration of the transmissions and acknowledgement waits of the given frame itself. Since, in the event of a collision, the hosts involved in the collision do not restart to sense the channel until after an acknowledgement timeout ($ACKt$), this delay component comes to suc plus $(col + ACKt)$ times the expected number of collisions of the given frame, which is $\frac{p_H}{1-p_H}$ or $\frac{p_L}{1-p_L}$, respectively. Adding this to the delay components due to backoff which were computed above, we finally obtain the expression for the average delay of a high-power or low-power frame, respectively:

$$D_H = X_H\{emp + [(s_H \cdot t_H + s_L \cdot t_L) \cdot suc + (t_H(1-s_H) + (1-t_H)t_L(1-s_L)) \cdot col]/[(1-t_H)(1-t_L)]\} + suc + \frac{p_H}{1-p_H}(col + ACKt) \quad (24)$$

$$D_L = X_L\{emp + [(s_H \cdot t_H + s_L \cdot t_L) \cdot suc + (t_H(1-s_H) + (1-t_H)t_L(1-s_L)) \cdot col]/[(1-t_H)(1-t_L)]\} + suc + \frac{p_L}{1-p_L}(col + ACKt) \quad (25)$$

Figure 2 plots the delay in each power class, as a function of the number of high-power hosts. As expected, the delay for high-power frames is consistently lower than that for low-power ones, for any proportion of high-power hosts in the LAN, since a high-power frame is less likely to suffer a collision. Furthermore, we note that the delay of high-power hosts is not significantly higher than in the single-power case (i.e. if the low-power hosts were silent altogether), which further reinforces the viability of the dual-power approach for prioritising of delay-dependent applications (such as voice). As for the low-power hosts, we again note a similar effect to that observed for the throughput performance, namely, that their delay does not monotonically degrade in the number of high-power ones: indeed, from a certain point, increasing the proportion of high-power hosts surprisingly improves the delay of the remaining low-power ones. Again, we explain this by the fact that, with a higher number of high-power hosts, their

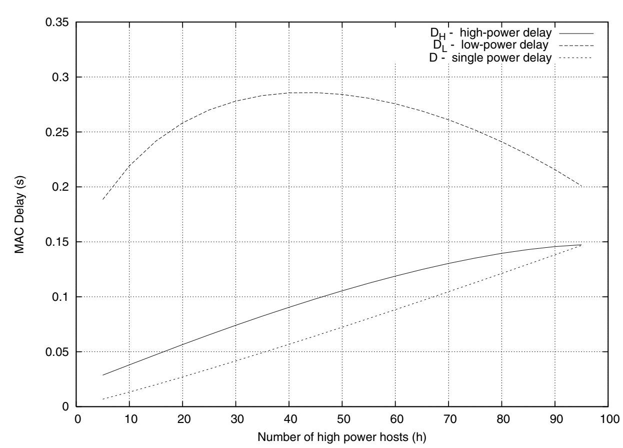

Fig. 2. Average MAC delay for each of the power classes.

average backoff duration gets longer, leaving more free slots for successful transmissions of low-power frames.

C. Dependence on Transmission Power Ratio

In this section we study the impact of the power ratio on service differentiation. For concreteness, we use a capture threshold ratio of $z_0 = 10$dB, which is a commonly used value for the minimum SIR (including the spread-spectrum coding gain) required for correct reception [12]; however, our qualitative results hold with any other capture thresholds as well.

Figure 3 shows the ratio between the average throughput achieved by a high-power host and that of a low-power one, for several selected values of the transmission power ratio. Similarly, Figure 4 shows the differentiation ratio for the average delay. Both figures clearly demonstrate, as expected, that the differentiation between the two power classes grows monotonically with the power ratio; this supports our view that the limit case, considered in the previous sections, provides an upper bound on the differentiation that can be achieved by employing a dual transmission power. It is also clear that the differentiation factor diminishes as more hosts use high power — an effect that is expected in any system offering two levels of priority, as more hosts compete for the higher-priority service. Furthermore, we observe that a sizeable differentiation is achieved even for power ratios that are not very large; for example, a transmission power ratio of just 10 suffices to improve the throughput and the average delay of high-priority hosts by a factor of 2.5, when $h = 10$. Also the differentiation increases more slowly for higher values of the power ratio (e.g., the performance difference between a ratio of 200 and that of 1000 is quite small). This finding is encouraging and suggests that QoS differentiation using different power levels is a viable approach, and can be achieved without imposing a very high cost on energy consumption.

IV. Conclusion

We have studied the performance of capture based service differentiation in IEEE 802.11 wireless LANs. By deliberately enhancing capture through a dual transmission power scheme, we have demonstrated the effectiveness of such a system for quality-of-service (QoS) differentiation. Since our approach requires no modifications to existing hardware, unlike most other proposals for QoS support in wireless LANs (e.g. the EDCA favoured in the emerging IEEE 802.11e standard), we argue that it can be readily deployed. Nevertheless, designing a detailed practical protocol that would allow the access point to control the transmission powers of the other hosts, so as to achieve a desired QoS level, is left as an important subject for further work.

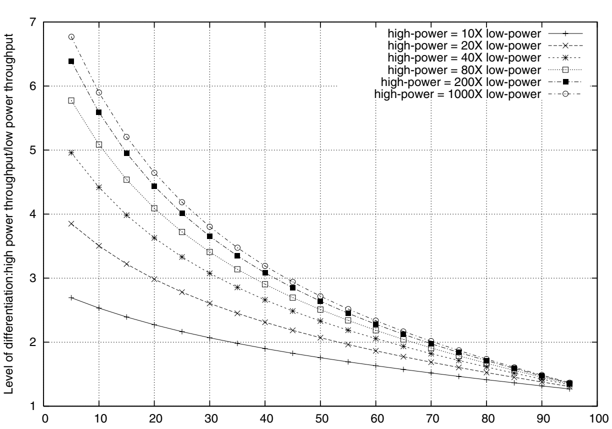

Fig. 3. Throughput differentiation with different transmission power ratios.

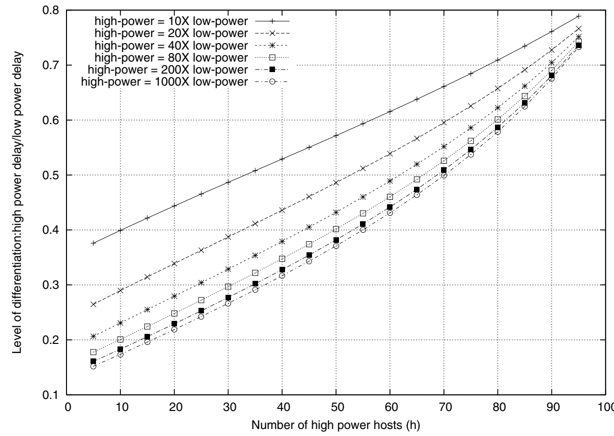

Fig. 4. Average MAC delay for each of the power classes.

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