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Detection for Medium Access Control in Random Access CDMA

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Abstract — **We consider a reservation-based medium access control (MAC) scheme where users reserve data channels through a slotted-ALOHA procedure. The base station grants access to users in a Rayleigh fading environment using detectors that utilize measurements at the physical layer and system information at the MAC layer. The performance analysis is based on a Markov Chain formulation with the states being defined by the number of busy and locked channels. MAP detectors with cost optimized for throughput are presented. Also considered is a Neyman-Pearson-like detector with false-alarm rate optimized for MAC throughput.**

I. Introduction

Detection plays a key role in Medium Access Control (MAC) of random access networks. In UMTS-WCDMA [6], for example, a random access scheme is used for channel (code) reservation. Users attempt reservation by transmitting a signature randomly chosen from a pool of available codes. The base station grants or denies transmission based on the measured signal strength. Collision occurs if more than one users send requests for a code and that code is acknowledged. On the other hand, if a code is acknowledged while no user sends request, the code is mistakenly taken out of the pool of available codes for other users, which causes an inefficient channel (code) utilization and heavier traffic, more frequent collisions in other channels.

It is not obvious that the classical approach to optimal detection based on trade-offs of misdetection and false alarm naturally leads to optimal MAC performance. Here, we must take into account properties of the arrival process and the impact of collision on throughput and delay. To this end, the literature is scarce; only a few ad hoc schemes have been reported [2, 3, 7].

Motivated by the idea of cross layer design of signal detection and MAC, we consider the detection and acknowledgement strategies for a CDMA random access network with transmissions undergoing flat Rayleigh fading. Focusing on the detector design, we exploit information from measurements at the physical layer, the traffic statistics, and the network states at the MAC layer.

The paper is organized as follows. We describe the system model in Sec.II where basic functions and assumptions are presented separately for mobile and base stations. In Sec.III, a throughput analysis is presented using a Markov chain formulation. Detector design is considered in Sec.IV where we present several detectors optimized for throughput. We conclude after discussing the results of simulations in Sec.V.

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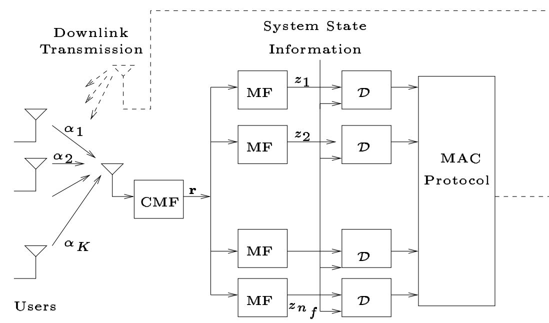

Fig. 1: A reservation-based random access in CDMA. CMF: Chip-matched-filtering and sampling. MF: Code matched filter.

II. System Model

The system considered here is similar to that used in the random access channel (RACH) in WCDMA [6] and is illustrated in Fig. 1.

A The Mobile Stations

The random access scheme is based on slotted ALOHA channel reservation. At the beginning of each slot, the base station broadcasts a set $\mathcal{C}$ of available orthogonal preamble signatures for the uplink reservation. An interested user transmits a randomly selected signature from $\mathcal{C}$ and waits for an acknowledgement. If a positive acknowledgement is received, the user proceeds to transmit data using an orthogonal code having a one-to-one relationship with the preamble signature. If a channel is acknowledged when two or more users are attempting access, a collision occurs and the channel becomes *locked* i.e., it is unavailable to the other users even though the channel is not contributing to the throughput. We further note that a channel might get locked when the base station transmits an ACK even when no user is attempting access. In case no acknowledgement is received, the user backs off and retries after a random delay. We assume that no preamble power ramping is carried out *i.e.,* a user does not increase power on retries.

We assume that the access attempts that include new arrivals as well as retries lead to a Poisson process with intensity λ attempts/slot. The Poisson assumption is an approximation used here as in [2, Ch. 3-4] for tractable analysis.

We further assume that, once a signature is acknowledged, the user transmits a data packet of size L slots, L being geometrically distributed with mean $E(L) = 1/l$ slots. Thus an occupied channel becomes free in the next slot with probability l. We also assume that a channel locked due to collision becomes free in the next slot with the same probability l. On the other hand, a channel unavailable due to false alarm is assumed to become available in the very next slot.

B The Base Station

After announcing the available preamble signatures $\mathcal{C}$, the base station performs matched filtering for each code in $\mathcal{C}$. The output of each matched filter is used in some form of hypothesis testing (denoted as $\mathcal{D}$), and the MAC protocol makes decisions on acknowledgement based on the outcome of the test.

To assemble the set of available preamble signatures for the next slot, the base station first takes out those codes acknowledged in the current slot. It then checks whether those occupied codes has become free, and adds those released codes to the new signature pool. For simplicity, we assume that there is no error made in determining whether a code is still in use.

We emphasize that the size of $\mathcal{C}$ varies from slot to slot, which makes the attempt rate time varying at each channel (even though the overall attempt rate is constant). The fluctuation of the available signatures makes detection thresholds time varying. This makes the optimal detection problem nontrivial.

III. MAC Performance

Given the traffic model of the previous section, the MAC performance in terms of channel occupancy can be evaluated through a Markov chain, the formulation of which is the aim of this section. Since the performance metric is channel occupancy, for each slot, we need to keep track of the number of busy channels *i.e.,* channels which are carrying data. We should also keep track of the number of channels locked due to collision and false alarm. These numbers directly influence the number of channels that are actually available in a slot which in turn influences the effective arrival rate per channel. It will be seen later that the number of free channels is a key parameter needed by a detector to optimize performance at the network level. We, thus, define a state i in the Markov Chain by (n_{bi}, n_{li}, n_{0i}), where n_{bi} is the number of busy channels when in state i, n_{li} is the number of channels locked as a result of a collision, and n_{0i} is the number of channels locked due to false alarm. Thus, a user wishing to access needs to choose from $N_c - n_{bi} - n_{li} - n_{0i} = n_{fi}$ free signatures (channels).

In order to obtain the transition probabilities, $P_{ij} = P(j|i) = P(n_{bj}, n_{lj}, n_{0j}|n_{bi}, n_{li}, n_{0i})$, we define: n_{bp} - number of free channels that become busy in the next slot, n_{bm} - number of busy channels that become free in the next slot, n_{lp} - number of free channels that become locked due to collision in the next slot, n_{lm} - number of channels locked due to collision that become free in the next slot, n_{0p} - number of free channels that become unavailable in the next slot due to a false alarm, and n_{0m} - number of channels unavailable due to false alarm that become free. We must have:

$$n_{bj} = n_{bi} + n_{bp} - n_{bm}, \quad (1)$$
$$n_{lj} = n_{li} + n_{lp} - n_{lm}, \quad (2)$$
$$n_{0j} = n_{0p}. \quad (3)$$

The last equality follows from the fact that $n_{0i} = n_{0m}$, since the channels locked due to false alarm become available in the very next slot. And thus we get:

$$P_{ij} = \sum_{A} P(n_{bp}, n_{lp}, n_{0p}|n_{fi}, \mathcal{D}) P(n_{bm}|n_{bi}) P(n_{lm}|n_{li}), \quad (4)$$

where A is the set of $\{n_{bp}, n_{bm}, n_{lp}, n_{lm}, n_{0p}\}$ satisfying the identities noted above. Notice the conditioning in the various terms on the right hand side. Channels that are busy/locked become free independently of the other channels. The probabilities are governed only by the statistics of the packet size. The first term on the right hand side, however, depends heavily on the detector design. Given the number of free channels, if the arrival statistics at each channel are independent of those at the others (which is the case in the premise of this paper), the detector for each channel can function independently. Thus, in order to obtain $P(n_{bp}, n_{lp}, n_{0p}|n_{fi}, \mathcal{D})$, it is sufficient to obtain (i) $P_b(n_{fi}, \mathcal{D})$, the probability that a free channel becomes busy in the next slot due to a successful access attempt, (ii) $P_l(n_{fi}, \mathcal{D})$, the probability that a free channel becomes locked in the next slot as a result a of a collision, and (iii) $P_0(n_{fi}, \mathcal{D})$, the probability that a free channel becomes unavailable for the next slot due to a false alarm. Note again that the probabilities so described are dependent on the detector strategy used. Given these we have:

$$P(n_{bp}, n_{lp}, n_{0p}|n_{fi}, \mathcal{D}) = \frac{n_{fi}!}{n_{bp}! n_{lp}! n_{0p}! \tilde{n}!} P_b^{n_{bp}}(n_{fi}, \mathcal{D}) \times P_l^{n_{lp}}(n_{fi}, \mathcal{D}) P_0^{n_{0p}}(n_{fi}, \mathcal{D}) \tilde{P}^{\tilde{n}} \quad (5)$$
$$P(n_{bm}|n_{bi}) = \binom{n_{bi}}{n_{bm}} l^{n_{bm}} (1-l)^{(n_{bi}-n_{bm})} \quad (6)$$
$$P(n_{lm}|n_{li}) = \binom{n_{li}}{n_{lm}} l^{n_{lm}} (1-l)^{(n_{li}-n_{lm})}, \quad (7)$$

where

$$\tilde{n} = n_{fi} - (n_{bp} + n_{lp} + n_{0p}), \quad (8)$$
$$\tilde{P} = 1 - (P_b(n_{fi}, \mathcal{D}) + P_l(n_{fi}, \mathcal{D}) + P_0(n_{fi}, \mathcal{D})). \quad (9)$$

The equilibrium distribution of states, p_i, can be obtained from (4)-(7); the channel occupancy or the normalized throughput, $S_\lambda(\mathcal{D})$, can now be written as:

$$S_\lambda(\mathcal{D}) = \frac{1}{N_c} \sum_i p_i n_{bi} \ . \quad (10)$$

The superscript denotes the dependence of the throughput on λ, the arrival rate. The problem that now faces us is that of designing a detector that will maximize S_λ. We can state the problem informally as: *Design a detector and acknowledgement strategy so as to obtain the optimal probabilities -* $P_b(n_{fi})$, $P_l(n_{fi})$, $P_0(n_{fi})$ *- which maximize the channel occupancy.* If we denote the optimal detection strategy by $\mathcal{D}_0$, we have:

$$\mathcal{D}_0(\lambda) = \arg\max_{\mathcal{D}} S_\lambda(\mathcal{D}) \quad (11)$$

The problem is different from problems considered in classical detection literature. Though the probabilities can be related to the classically defined probabilities of detection and false alarm, they are not the same and we do not know how they affect the network throughput. We observe that, even if a closed form relationship were to exist between detector design parameters and the probabilities - $P_b(n_{fi}), P_l(n_{fi}), P_0(n_{fi})$ - no such relationship would exist between the throughput and the detection design parameter. Thus, any optimization will have to be carried out numerically through a lookup search over the design parameter space. Fortunately, the entire procedure can be carried out offline and before hand so that given a scenario, the optimal detection strategy is immediately available. We next consider the signal model and study the detector and acknowledgement strategy design problem formally.

IV. The Detector

The detection considered here differs from the classical detection problem in two aspects. First, our objective is to maximize the network throughput. Second, the detector needs to exploit the system state information (*e.g.,*number of available channels). The challenge is that detection errors affect the system state which in turn affects the statistics of the incoming traffic.

A The Signal Model

Consider the model depicted in Fig.1. Each available channel has a detector associated with it. The detector takes as its input the sampled chip-matched filtered signal. We assume that the transmitted signal undergoes Rayleigh flat fading, the Rayleigh parameter having the same value for each user. Assume that n_f channels are available and K users contend for reservation. The sampled output of the chip-matched filtered can be written as:

$$\mathbf{r} = \sum_{k=1}^{K} \alpha_k \mathbf{s}_k + \mathbf{w} \tag{12}$$

where α_k are the complex amplitudes which are i.i.d. with distribution $\mathcal{C}N(0, \sigma_d^2/2N^2)$, N is the signature length in chips, σ_d^2 the SNR. All the symbols in bold font denote vectors of length N. The signatures, $\mathbf{s}_k$, belong the set of available orthogonal signatures, $\mathcal{C} = \{\mathbf{c}_1, \mathbf{c}_2, ..., \mathbf{c}_{n_f}\}$. The elements of $\mathcal{C}$ have a one-to-one relationship with the set of available channels and $\mathbf{c}_i^H \mathbf{c}_i = N$ for $i = 1, 2, ..., n_f$ (H denotes the hermitian operator). The noise $\mathbf{w}$ is AWGN with distribution $\mathcal{C}N(0, 1/2N\mathbf{I})$.

At the i^{th} detector, decorrelating with the signature $\mathbf{c}_i$ we get:

$$\begin{aligned} z_i &= \mathbf{c}_i^H \mathbf{r} \qquad (13) \\ &= \sum_{k:\mathbf{s}_k = \mathbf{c}_i} N\alpha_k + w_i = x_i + w_i \qquad (14) \end{aligned}$$

where $x_i \sim \mathcal{C}N(0, K_i\sigma_d^2/2)$ is the component due to K_i number of users selecting signature $\mathbf{c}_i$ and $w_i \sim \mathcal{C}N(0, 1/2)$. At this point we may drop the subscript i for the detector, because given n_f, the working of each detector is identical to the rest. Notice that $|z|^2$ is a sufficient statistic that can be generated from z and that $|z|^2$ has an exponential distribution. For ease of notation we will refer to $|z|^2$ as y from this point onwards. Based on the above statistic the detector must make a decision on whether or not a single user is attempting access.

Formally, consider the following [1]- parameter set defined by the user indices $\Lambda = \{0, 1, 2, 3, ..\}$; random parameter†, Θ, taking on values in Λ. The realization, θ, is the number of users attempting reservation of the same channel. The decision rule should be based on y. We have the following to work with - conditional distribution of y given $\Theta = \theta$:

$$p(y|\theta) = \frac{1}{\theta\sigma_d^2 + 1} \exp\left(\frac{-y}{\theta\sigma_d^2 + 1}\right) . \tag{15}$$

†Note that Θ is not a design parameter, the design parameter η appears later in the discussion.

Since the arrivals are Poisson, given that n_f channels are free, the access attempt rate for a particular channel is $\lambda_f = \lambda/n_f$. Thus, the prior probability for θ given the arrival rate can be written as

$$w(\theta) = \exp(-\lambda_f)\frac{(\lambda_f)^\theta}{\theta!} . \tag{16}$$

B The Bayesian Detector

We first consider the MAC protocol based on the binary hypothesis on the number of users transmitting a particular preamble. Specifically,

$$\begin{aligned} H_0 &: \theta \in \{0, 2, 3, \cdots\} \triangleq \Lambda_0 \\ H_1 &: \theta \in \{1\} \triangleq \Lambda_1 . \qquad (17) \end{aligned}$$

Notice that H_0 is a composite hypothesis.

The Bayesian detector has the form

$$\delta(y) = \begin{cases} 1 & > \\ 0 \ or \ 1 \quad \frac{P(\Theta\in\Lambda_1|y)}{P(\Theta\in\Lambda_0|y)} & = \quad \eta(n_f) \\ 0 & < \end{cases} \tag{18}$$

where $\eta(n_f)$ is the 'cost-ratio' dependent on the number of free channels as noted above. Now, since the cost-ratios are actually unknown, we might try a lookup search for the optimal $\eta(n_f)$ with $n_f = 1, 2, ..., N_c$. In order to simplify the lookup search, we assume that the cost-ratio remains fixed for different n_f. This simplification should result in sub-optimality.

For the present model, we have:

$$\frac{P(\Theta \in \Lambda_1|y)}{P(\Theta \in \Lambda_0|y)} = \frac{\frac{1}{\sigma_d^2+1}\exp\left(\frac{-y}{\sigma_d^2+1}\right)\lambda_f}{\sum_{\theta\neq 1}\frac{1}{\theta\sigma_d^2+1}\exp\left(\frac{-y}{\theta\sigma_d^2+1}\right)\frac{\lambda_f^\theta}{\theta!}} . \tag{19}$$

Given cost-ratio η and access rate λ_f (both might have dependence on n_f), we can numerically determine the decision regions, $\Gamma_1(\eta, \lambda_f)$ and $\Gamma_0(\eta, \lambda_f)$ corresponding to the two hypotheses. The decision regions are of the form:

$$\begin{aligned} y \in \Gamma_1(\eta, \lambda_f) & \quad \text{if } \tau_1(\eta, \lambda_f) \leq y \leq \tau_2(\eta, \lambda_f) \qquad (20) \\ y \in \Gamma_0(\eta, \lambda_f) & \quad \text{otherwise} \qquad (21) \end{aligned}$$

where $\tau_1(\eta, \lambda_f)$ and $\tau_2(\eta, \lambda_f)$ can be interpreted as power thresholds based on which the detector makes its decisions. Intuitively, we would expect the decision regions to be of the form given in (20), so that power falling below the lower threshold corresponds to the case of no user attempting access, while power falling above the upper threshold corresponds to the case of two or more users attempting access.

In Fig.2, we show the thresholds as a function of access rate λ_f for SNR's of 5 dB and 10 dB. Plotted in Fig.3 is the variation of thresholds v/s SNR for $\lambda_f = 0.5$ The upper threshold τ_2 decreases as the SNR decreases and as λ_f increases, which is intuitive. What is surprising is the variation of the lower threshold τ_1 which is not very sensitive to λ_f or the SNR. Against intuition, it does not go down as the λ_f increases.

Having obtained the decision regions, we can now obtain the event probabilities needed for the Markov chain formulation.

As defined before $P_0 = \Pr\{$ A particular free channel becomes locked in the next slot due to false alarm$\}$. The aforementioned event occurs when the received signal power lies

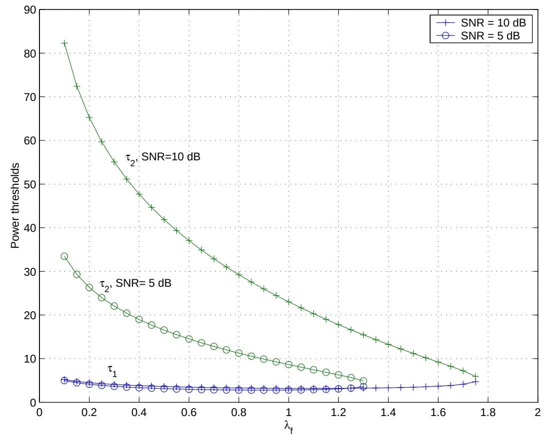

Fig. 2: Thresholds vs. access rate λ_f for SNR = 5 dB and 10 dB

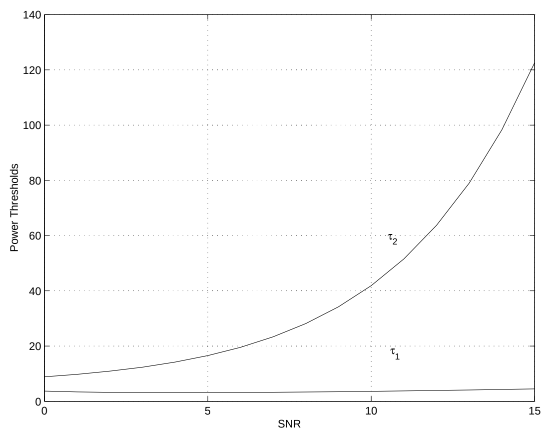

Fig. 3: Thresholds vs. SNR for $\lambda_f = 0.5$

between the two thresholds with no user present. And thus the event probability is given by:

$$P_0(n_f, \eta) = e^{-\lambda_f} \left(e^{-\tau_1} - e^{-\tau_2} \right) . \quad (22)$$

Note that τ_1, τ_2 above are dependent on η, SNR σ_d^2, and λ_f (and therefore, n_f). A channel can also become locked if two or more users attempt access and are ACKed. The probability that channel gets locked due to collision between users is given by:

$$P_l(n_f, \eta) = \sum_{k=2}^{\infty} \frac{e^{-\lambda_f} (\lambda_f)^k}{k!} \left(e^{-\tau_1/(k\sigma_d^2+1)} - e^{-\tau_2/(k\sigma_d^2+1)} \right) . \quad (23)$$

We have defined $P_b = \Pr\{$ A particular free channel becomes occupied in the next slot$\}$. A channel gets occupied if only one user attempts access and the received power level falls within the two thresholds. Therefore:

$$P_b(n_f, \eta) = \lambda_f e^{-\lambda_f} \left(e^{-\tau_1/(\sigma_d^2+1)} - e^{-\tau_2/(\sigma_d^2+1)} \right) . \quad (24)$$

Given λ, η, N_c, and σ_d^2, we know we can compute the various event probabilities and therefore the channel occupancy as defined in (10). Optimization now simply involves finding the η that maximizes the throughput for a given λ. Denoting the optimal cost-ratio by η_o we have:

$$\eta_o = \arg\max_{\eta} S_\lambda(\eta) . \quad (25)$$

C The Multi-hypotheses MAP

The binary MAP does not admit a closed form expression for thresholds; numerical optimization must be carried out for different traffic rates and available free channels. We, thus, consider another class of detectors for which the decision regions can be determined without resort to numerical computations. The detector is actually a multi-hypotheses MAP detector (as opposed to the Binary MAP detector, which is just the Bayesian detector with $\eta = 1$) which optimally detects the number of users attempting access based on the a posteriori probabilities of each $\theta \in \Theta$. The detector basically gives $\hat{\theta} = \arg\max_\theta p_\theta(y)w(\theta)$. The MAC protocol can then make a decision based on $\hat{\theta}$. H_1 will be held to be true when $\theta = 1$ has the maximum a posteriori probability amongst all $\theta \in \Theta$ i.e., when:

$$\arg\max_{\theta} p_\theta(y)w(\theta) = 1 . \quad (26)$$

For the Multi-hypotheses MAP detector it can be shown that $\tau_1(\lambda_f)$ and $\tau_2(\lambda_f)$ are determined by:

$$\tau_1(\lambda_f) = \frac{\sigma_d^2+1}{\sigma_d} \log\left(\frac{\sigma_d^2+1}{\lambda_f}\right) \quad (27)$$

$$\tau_2(\lambda_f) = \frac{(\sigma_d^2+1)(2\sigma_d^2+1)}{\sigma_d^2} \log\left(\frac{2(2\sigma_d^2+1)}{\lambda_f(\sigma_d^2+1)}\right) . \quad (28)$$

The first threshold is determined by comparing the a posteriori probabilities for $\theta = 1$ and $\theta = 0$. Similarly, the second threshold is comparing the a posteriori probabilities for $\theta = 1$ and $\theta = 2$. The identities hold for reasonable values of the arrival rate but breakdown when λ_f is too large. For example, $\tau_1(n_f)$ becomes negative when λ_f exceeds $\sigma_d^2 + 1$.

D A Neyman-Pearson-Like Detector

We compare the class of Bayesian detectors with fixed cost-ratio with the class of single threshold detectors which acknowledge a channel when the power exceeds a given threshold (the upper threshold $\tau_2 = \infty$, which is essentially equivalent to assuming that the SNR is high). The detectors discussed in the literature available on RACH [3] belong to this class. We consider a subclass of single threshold detectors defined by design parameter α which is the maximum probability of 'false-alarm' allowed. The optimization here involves searching for the α that gives the maximum throughput for a given λ. For a given threshold τ and effective arrival rate into channel, λ_f, we can find the detection and 'false-alarm' probabilities‡, $P_D(n_f)$ and $P_F(n_f)$, respectively, as:

$$P_D(n_f) = e^{-\tau/(\sigma_d^2+1)} \quad (29)$$

$$P_F(n_f) = \frac{1}{1-\lambda_f e^{-\lambda_f}} \sum_{k\neq 1} \frac{\lambda_f^k e^{-\lambda_f}}{k!} e^{-\tau/(k\sigma^2+1)} . \quad (30)$$

The Neyman-Pearson-like formulation involves finding $\tau(n_f, \alpha)$ such that $P_D(n_f)$ is maximized subject to constraint

‡These probabilities are w.r.t the definition of the two hypotheses and corresponding parameter sets. They are different from P_b and P_0 defined earlier.

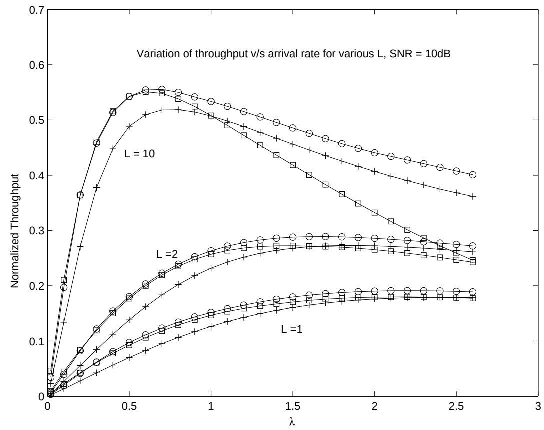

Fig. 4: Normalized Throughput vs. Arrival rate for various detectors with $L = 1, 2, 5,$ and 10. SNR = 10dB. Bayesian($\circ$), Single threshold($\square$), Multi-hypotheses MAP($+$)

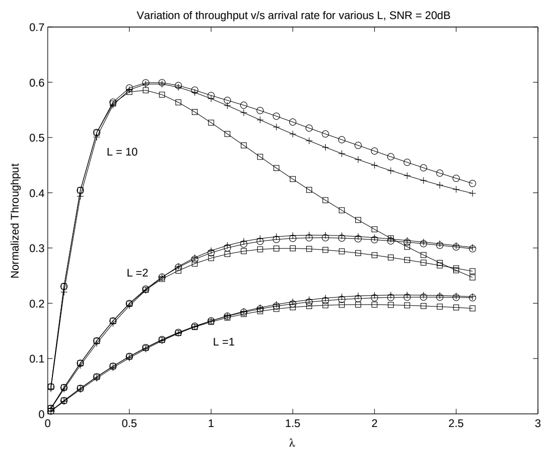

Fig. 5: Normalized Throughput vs. Arrival rate for various detectors with $L = 1, 2, 5,$ and 10. SNR = 20dB. Bayesian($\circ$), Single threshold($\square$), Multi-Hypotheses MAP($+$)

that $P_F(n_f) \leq \alpha$. Once $\tau(n_f, \alpha)$ is known for $n_f = 1, 2, ..., N_c$ we can determine the event probabilities needed for obtaining the throughput ($S_\lambda(\alpha)$) as in (22)-(24), by putting $\tau_1 = \tau$, $\tau_2 = \infty$.

As before, we need to optimize the throughput over the design parameter, which, in this case, is α. Again, a lookup search needs to be carried out to obtain the optimal α_0 as in:

$$\alpha_0 = \arg\max_{\alpha} S_\lambda(\alpha) \tag{31}$$

V. Simulation Results

We now compare the performance of the various detector classes. Figs.4,5 show the throughput plots versus arrival rate for SNR = 10dB, 20dB, respectively. As expected, throughput is better for higher SNR.

We see that none of the detector classes performs consistently better than the others. The Bayesian detector class does the best for most cases. However, the Multi-hypotheses MAP betters its performance for higher SNR. We note that the optimal detector scheme is not yet within reach. The peak

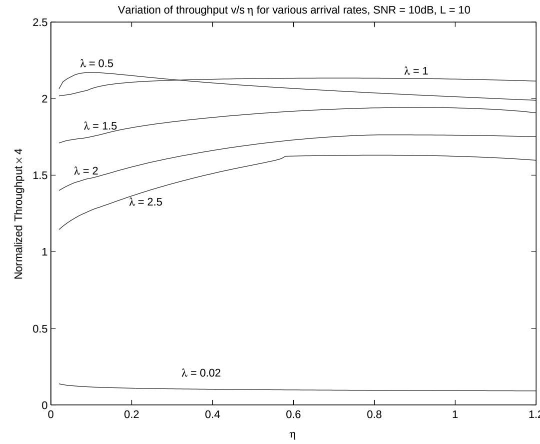

Fig. 6: Normalized Throughput vs. η for the Bayesian detector. SNR = 10dB, L = 10, for various λ

(over all arrival rates) throughput obtained with all the detectors is almost the same. The single threshold strategy is detrimental for high arrival rates as it hinders the possibility of NACKing for the collision case. As expected, throughput increases with increasing SNR and L (the mean packet size).

Fig.6 show the variation of throughput v/s η for the Bayesian detector. Varying the cost-ratio does not vary the throughput significantly, we could have as well worked with $\eta = 1$ which corresponds to the MAP detector. However, low η is generally not good when λ is high; smaller η leads to a smaller τ_1 and a larger τ_2, which in turn increases both the false alarm rate as well as the collision rate.

VI. Conclusion

The random access CDMA channel presents us with the interesting problem of detector design for increasing the throughput. The problem cannot and should not be considered in a classical sense. The detector needs to consider not only the signals as transmitted by users but also whatever system state knowledge it can obtain. In the scenario we have considered, it is difficult to obtain closed form relationship between the detector design parameters and the performance measure (the normalized throughput). We have considered three classes of detectors: one is the class of classical Bayesian detectors where we assume that the unknown cost-ratio is fixed, the second is the class of single threshold detectors which are used in practice and the third which is a Multi-hypotheses MAP detector. Given the arrival rate, the class of Bayesian detectors gives a better alternative to that given by the class of single threshold detectors or the approximate MAP detector for most cases. However, no single class gives us the optimal detector which as of now is out of reach.

We cannot be sure if the performance of any class is near the optimal performance possible. Also, the scenario we have considered is very restricted. We need to broaden the scope and develop analytical methods for more varied scenarios allowing better understanding of the interplay between the MAC and physical layers.

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