Network-level QoS Assurances Through Adaptive Allocation of CDMA Resources

Moncef Elaoud[†] Bechir Hamdaoui[‡] Parameswaran Ramanathan[‡]

[†] Computer Communications Research Lab
Telcordia Technologies Inc.
Piscataway, NJ 08854-4156.

[‡]Department of Electrical and Computer Engineering
University of Wisconsin-Madison
Madison, WI 53706–1691
E-mails: hamdaoui@cae.wisc.edu, parmesh@ece.wisc.edu
E-mail: moncef@research.telcordia.com

ABSTRACT

In a Code Division Multiple Access (CDMA) network, multiple Mobile Hosts (MHs) can simultaneously transmit over the wireless channel by using different codes. To assure an acceptable Quality of Service (QoS) for all MHs' flows, the network usually tunes the transmit powers of all MHs to achieve a certain level of signal strength as compared to the noise and the interference (SINR) for each MH. The traditional assumption in power control schemes is that the SINR requirement is statically determined for each MH's flow.

In contrast, in this paper, we propose a scheme that dynamically adapts the SINR requirements of MH's flow based on its QoS requirements and the conditions of the wireless channel between the MHs and the base station. As a result of this adaptation, we show that network-level QoS measures such as fraction of packets meeting their delay requirements and energy consumed per packet transmission are significantly better than in a scheme that statically fixes the SINR requirements. We show that the adaptation approach works well for the Matched Filter (MF) and the Minimum Mean Squared Error (MMSE) receivers.

Our scheme uses a simple table-driven approach for optimally selecting the target SINR requirement for each MH at run time. The entries in the table are computed off-line using a dynamic programming algorithm with the objective of maximizing a profit function that balances the need for meeting the network-level QoS requirements and the cost of using a particular target SINR for a given transmission.

Key Words: adaptive allocation scheme, fixed allocation scheme, SINR, MMSE receiver, Matched Filter (MF) receiver, QoS, optimal profit function.

1 Introduction

In a Code Division Multiple Access (CDMA) network, each Mobile Host (MH) is assigned a unique spreading code to modulate its data bits prior to transmitting them over the wireless channel. Multiple MHs can simultaneously transmit and still reliably deliver the data bits to the recipients. At the receiver, knowledge of the transmitter's spreading code is used to decode the received data bits.

The decoding of the data bits at the receiver is not always error-free. Errors typically occur when the strength of the received signal from the sender is not sufficiently large relative to the sum of the noise and signal strengths of other MHs. The ratio of the strength of the desired signal to that of the noise and the other signals is usually called the *Signal to Interference and Noise Ratio* (SINR). The lower the SINR, the higher the probability of bit error, which in turn usually means a higher probability of uncorrectable errors in a packet. As a result, SINR is often used as a measure of Quality of Service (QoS) at the physical layer. Specifically, each MH's flow is assumed to have a fixed SINR requirements representing its QoS needs and the CDMA system strives to meet the SINR requirements of all flows.

To meet all the SINR requirements, a CDMA network usually employs a *power control scheme*. In a power control scheme, the transmit powers of all MHs are repeatedly adjusted to satisfy the SINR requirements of all flows. Informally, increasing the transmit power of a MH increases the strength of the received signal at the intended receiver which in turn, increases the SINR. However, this increase in signal strength also increases the interference for other MHs. Therefore, a power control scheme carefully adjusts the transmit powers of MHs to satisfy their SINR requirements.

The power control problem in CDMA networks is well-studied in the literature [1–18]. Some of the solutions are centralized, where a base station computes the transmit powers for all MHs to meet a certain objective [2–11]. For example, in [2], the aim is to decrease the bit-error-rate by coordinating transmission powers of MHs in different cells. The approach in [4, 7, 9, 14] aims at minimizing the sum of transmitted powers of all MHs. The solution in [5] adjusts the transmit powers of all MHs to achieve a common target SINR value for all MHs. Other solutions are distributed [12–17]. In these solutions, each mobile host is given basic information on its last transmission. The information may include its path loss and the SINR as seen by the base station during the last transmission. Based on this information, each MH selects its transmission power to achieve its QoS requirement. In [13, 15], the transmit power is adjusted to achieve a common SINR for all MHs. Step power adjustments are used to achieve a minimum sum of transmitter powers over all MHs in [17].

Our goal in this paper is not to devise another power control scheme. Instead, we propose an approach that complements existing power control schemes to better meet the network-level QoS requirements of MH's flows. Specifically, we assume that the network-level QoS requirements of each flow translates to a deadline requirement for each of its packets. Instead of keeping the target SINR fixed, we adapt the SINR requirements of each flow based on the deadline requirement of its head packet and its current channel conditions. A power control scheme is then used to achieve the chosen target SINR. We show through simulations that as a result of this adaptation, there is a considerable increase in the number of MHs that can be supported in the system without violating QoS requirements. Also, there is a significant reduction in the average energy consumption per packet at a MH. We also show that our adaptive scheme performs better than the fixed scheme regardless the type of filter receiver implemented in the system, *Matched Filter (MF)* or *Minimum Mean Squared Error (MMSE) filter* receivers.

The rest of this paper is organized as follows. In Section 2, we describe our assumed architecture and detail the system model. The proposed solution approach is discussed in Section 3. A description of the simulation model is given is Section 4. An evaluation of the proposed solution relative to a non-adaptive strategy are presented in Section 5. The paper concludes in Section 6.

2 System Model

In this paper, we consider a single cell of a wireless network. The cell has a Base Station (BS) and N Mobile Hosts (MHs). Each MH is running an application that generates a stream of packets. To meet the QoS requirements of the application, we assume that each packet must be delivered to the BS within a certain deadline constraint associated with the packet. If the packet is not delivered within its deadline constraint, there is deterioration in the QoS perceived by the application. We assume that the amount of deterioration depends on the fraction of packets that do not meet their deadline constraints; the larger the fraction of missed deadlines, the more the deterioration.

The scheme proposed in this paper can be implemented either in centralized or decentralized fashion. In the centralized version, each MH communicates its QoS requirements to the BS. The BS then performs the following three steps. First, the BS implements the proposed algorithm to calculate the target SINR for each MH. Second, it uses a power control algorithm to determine the transmission power for each MH to achieve its target SINR. Third, it conveys the power level that each MH should use in its next transmission. In the decentralized version, the BS conveys certain feedback information to each MH and the MHs individually run the proposed algorithm to compute their target SINR and the power level that they should use in their next transmission. For simplicity of presentation, we consider a centralized scheme in this paper.

Our assumed wireless network architecture is as follows. We assume that each packet contains the deadline requirements of the next packet in the MH's queue. If the MH's queue is empty at the time of transmission of a packet, then the MH sends another short control packet conveying the deadline requirement of the newly arriving packet when it occurs. Despite the use of forward error correction codes in each packet, the BS may not always be able to correct all the errors that occur during the transmission of a packet. Depending on whether the errors in a packet are correctable or not, the BS sends an acknowledgment (ACK) (negative acknowledgment (NACK)) to the MH. In response to NACK, the MH retransmits the packet if its deadline has not already expired. Packets with expired deadlines are discarded.

Prior to transmitting the ACK and NACK packets, the BS uses the scheme proposed in this paper to choose a target SINR for the next transmission. As described later, this target SINR is based on the deadline requirements of the head packet and the state of the wireless channel between the MH and the BS. The target SINR is then used in a power control algorithm to compute the transmit power the MH must use in its next transmission. We assume that this transmit power information is conveyed to the MH in the ACK and NACK packets.

2.1 Wireless Channel

The state of a wireless channel is usually characterized by the Bit-Error-Rate (BER) a stream observes during a packet transmission. The BER in turn is a function of the Signal to Interference and Noise Ratio (SINR) for the corresponding MH. The SINR of a communication between a MH i and a BS depends on two main factors: the path loss $\mathcal{H}_i$ and the interference $\mathcal{I}_i$. The path loss $\mathcal{H}_i$ depends on the distance between the MH i and the BS, and objects/obstructions in the path between the MH i and the BS. The interference $\mathcal{I}_i$, on the other hand, depends on the relative locations and the powers of other nearby transmitters. The path loss and interference usually vary with time and, as a result, there is a considerable variation in the error rates observed in message packets transmitted over the wireless channel.

Specifically, the SINR for MH i in a given transmission can be expressed as in Equa-

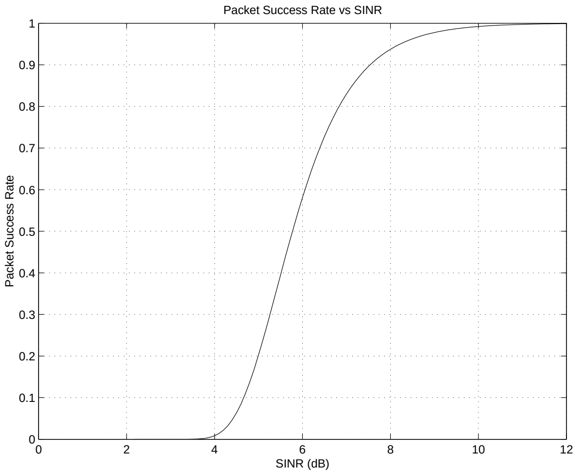


Figure 1: Packet Success Rate

tion (1).

$$\widehat{\gamma}_i = \frac{\mathcal{H}_i P_i}{\mathcal{I}_i + N_i} \tag{1}$$

where P_i is the transmit power of MH i, $\mathcal{H}_i$ is the path loss between MH i and the BS, $\mathcal{I}_i$ is the amount of interference for MH i, and N_i is the intensity of the noise in MH i's wireless channel. The interference $\mathcal{I}_i$ depends on the type of filter receiver used by the BS in decoding the bits of MH i. In this work, we considered both the Matched Filter and MMSE receivers. Both receivers' characteristics are well-studied in [18] and a brief description of their characteristics is given in Subsection 2.2.

Given $\widehat{\gamma}_i$, the average Bit-Error-Rate (BER) experienced by MH i in the corresponding transmission can be calculated depending on the channel model. In this paper, we assume that the relationship between BER and SINR is known. Depending on the forward error correcting code in the packet, a packet error rate can be computed given the BER [19]. Figure 1 shows the packet success rate (PSR) as a function of the signal to interference and noise ratio.

There are many schemes proposed in the literature for measuring and estimating the path loss and the interference experienced by each MH at the BS [20]. In this paper, we assume that the BS employs one of these scheme to estimate $\mathcal{H}_i$ and $\mathcal{I}_i$ for each MH i.

2.2 CDMA Receivers

In a spread-spectrum CDMA system, each MH is assigned a unique spreading code. Let S_i be the spreading code vector of MH i. Prior to transmitting its signal over the wireless channel, each MH i uses its spreading code to modulate its information bits. The knowledge of the spreading codes of all MHs permits the BS to discriminate a MH i's signal among others. The SINR for MH i is the ratio of MH i's energy to that of the noise plus other transmitters' energy at the output of the receiver [18], specifically, if G is the processing gain, then SINR:

$$\widehat{\gamma_i} = \frac{\mathcal{H}_i P_i (C_i^T S_i)^2}{\sum_{j=1,j\neq i}^{N} \mathcal{H}_j P_j (C_i^T S_j)^2 + (C_i^T C_i)\sigma^2} \tag{2}$$

where C_i, called filter coefficients, is a G dimensional vector characterizing the linear receiver for MH i, i.e., the demodulated MH i's symbol is $C_i Y$, where Y is the received signal.

Different receivers of varying complexity have been used at the base station. In this paper, we will be focusing on the Matched Filter (MF) and Minimum Mean Squared Error (MMSE) receivers.

2.2.1 Matched Filter Receiver

To demodulate MH i's signal, the MF receiver uses the spreading codes S_i as the filter coefficients C_i. Therefore, for such receiver, the SINR of MH i can be derived from Equation (2) by replacing C_i by S_i. It is shown in [18] that because the spreading codes are randomly and independently chosen, Equation (2) can then be approximated by Equation (3).

$$\widehat{\gamma_i} = \frac{\mathcal{H}_i P_i}{\frac{1}{G}\sum_{j=1,j\neq i}^{N} \mathcal{H}_j P_j + \sigma^2} \tag{3}$$

By matching Equations (1) and (3), the interference $\mathcal{I}_i$ and the noise N_i experienced by MH i's signal in its wireless channel are:

$$\mathcal{I}_i = \frac{1}{G}\sum_{j=1,j\neq i}^{N} \mathcal{H}_j P_j, \tag{4}$$

and

$$N_i = \sigma^2 \tag{5}$$

2.2.2 Minimum Mean Squared Error Receiver

In the MMSE receiver, the spreading codes of all the interfering MHs are taken into consideration in filtering MH i's signal, thus providing a better interference suppression capability as compared to the MF receiver. The filter coefficient vector, C_i, for MH i is optimized so that it maximizes the SINR. This optimal vector, C_i^*, is given by:

$$C_i^* = \arg \max_{C_i \in \Re^G} \frac{\mathcal{H}_i P_i (C_i^T S_i)^2}{\sum_{j=1, j \neq i}^{N} \mathcal{H}_j P_j (C_i^T S_j)^2 + (C_i^T C_i)\sigma^2} \tag{6}$$

Thus, Equation 2 can be written as:

$$\widehat{\gamma}_i = \frac{\mathcal{H}_i P_i}{\sum_{j=1, j \neq i}^{N} \frac{\mathcal{H}_j P_j (C_i^{*T} S_j)^2}{(C_i^{*T} S_i)^2} + \frac{(C_i^{*T} C_i^*)\sigma^2}{(C_i^{*T} S_i)^2}} \tag{7}$$

From Equations (1) and (7), we see that the interference $\mathcal{I}_i$, can be expressed as:

$$\mathcal{I}_i = \sum_{j=1, j \neq i}^{N} \frac{\mathcal{H}_j P_j (C_i^{*T} S_j)^2}{(C_i^{*T} S_i)^2}, \tag{8}$$

and the noise, N_i as:

$$N_i = \frac{(C_i^{*T} C_i^*)\sigma^2}{(C_i^{*T} S_i)^2} \tag{9}$$

2.3 Power Control Scheme

As mentioned in Section 1, the goal of this paper is not to introduce a new power control scheme. Instead, the proposed approach complements existing power control schemes to better meet the network-level QoS requirements of MHs. Therefore, the proposed algorithm assumes that there exists a power control scheme such that given the computed target SINRs, a power vector can be calculated to achieve the desired SINRs. In this section, we present the power control scheme used in this work.

The aim of the power control scheme, discussed here, is to find the optimal transmit power used by each MH i such that (i) the total transmit powers of all MHs is minimized and (ii) the quality of service of each MH i is satisfied. Therefore, a power control problem can be translated to: (i) minimize $\sum_{i=1}^{N} P_i$ such that $P_i \geq 0$ for all MHs, and (ii) satisfy $\widehat{\gamma}_i \geq \gamma_i^*$ where γ_i^* is the target SINR of MH i. Recall that $\widehat{\gamma}_i$ is given by Equations (3) and (7) respectively for the matched filter and the minimum mean squared error receivers.

We define the following:

$$\mathcal{L}_{MF} = \sum_{i=1}^{N} \frac{\widehat{\gamma}_i}{G + \widehat{\gamma}_i} \tag{10}$$

and

$$\mathcal{L}_{MMSE} = \sum_{i=1}^{N} \frac{\widehat{\gamma_i}}{G(1+\widehat{\gamma_i})} \tag{11}$$

to be the *network load* for the MF-system and the MMSE-system respectively.

It is shown in [18] that for both receivers (MF and MMSE), a unique optimal power vector $[P_1, P_2, \ldots P_N]$ which minimizes the total transmitted power $\sum_{i=1}^{N} P_i$ exists if the network load, as defined in Equations (10) and (11), is less than one. The network is said to be *loaded* if the network load is equal to or greater than one. In this paper, we assume that the BS first computes this optimal power vector whenever feasible and conveys it to the MHs. If it is not feasible, i.e., the network load is larger than one, then we assume that the base station scales the SINR requirements of all MHs by a constant factor δ such that: $\sum_{i=1}^{N} \frac{\delta\widehat{\gamma_i}}{G+\delta\widehat{\gamma_i}} < 1$, if the system uses the MF receiver, and $\sum_{i=1}^{N} \frac{\delta\widehat{\gamma_i}}{G(1+\delta\widehat{\gamma_i})} < 1$, if the MMSE receiver is used instead, and computes the transmit powers accordingly.

MF receiver: Given $\mathcal{L}_{MF} < 1$, the optimal transmit power for each MH i satisfying the power control optimization problem described above is [19]:

$$P_i = \frac{w_i}{\mathcal{H}_i}\left(\frac{\sum_{j=1}^{N} w_j N_j}{1-\sum_{j=1}^{N} w_j} + N_i\right) \tag{12}$$

for $1 \le i \le N$; where $w_j = \frac{\gamma_j^*}{G+\gamma_j^*}$.

MMSE receiver: To find a power vector solution to the power control problem when the system uses a MMSE receiver, we need to proceed iteratively as described in [16]. At iteration $n+1$, perform the following two steps:

- Step 1: Given a power vector, $P^{(n)} = [P_1^{(n)}, P_2^{(n)}, \ldots P_N^{(n)}]$ determined at iteration n, the filter coefficients of each MH i are derived from:

  $$\widehat{C}_i = \frac{A_i^{-1}(P^{(n)})S_i}{S_i^T A_i^{-1}(P^{(n)})S_i} \tag{13}$$

  where $A_i(P^{(n)}) = \sum_{j=1, j\neq i}^{N} P_j^{(n)} \mathcal{H}_j S_j S_j^T + \sigma^2 I$; I is the identity matrix of dimension N.

- Step 2: The power vector $P^{(n+1)}$ is computed by using the coefficients of all MHs determined in step 1 and the power vector $P^{(n)}$ as follows:

$$P_i^{(n+1)} = \frac{\gamma_i^*}{\mathcal{H}_i} \left(\sum_{j=1, j \neq i}^{N} \mathcal{H}_j P_j^{(n)} (\widehat{C}_i^T S_j)^2 + \sigma^2 (\widehat{C}_i^T C_i) \right) \tag{14}$$

Ulukus et al. [16] show that if the target SINRs are feasible, then the algorithm described in step 1 and 2 converges to the unique minimum power vector solution to the power control optimization problem, given an initial power vector $P^{(0)}$ and initial filter coefficients $[C_1^{(0)}, C_2^{(0)} \ldots C_N^{(0)}]$.

2.4 Problem Statement

Consider a single cell of a CDMA network having a BS and N MHs. Given the deadlines of packets at the head of the queue in each MH and the state of the wireless channel between each MH and BS (i.e., given the estimate of the path loss and the interference and noise levels in the wireless channel between each MH and the BS), determine the best SINR vector $[\gamma_1^*, \gamma_2^*, \ldots, \gamma_N^*]$ with the following potentially conflicting objectives

- meet the deadline requirement of each packet,
- reduce the energy consumed per packet, and
- increase the system capacity (i.e., the number of MHs that can be supported for a given tolerance to deadline misses).

The target SINRs for each MH is selected from a set $\Gamma = \{\gamma^0, \gamma^1, \gamma^2, \cdots, \gamma^M\}$ of SINRs. In this set, γ^0 is a special SINR denoting *Deferment*. If $\gamma_i^* = \gamma^0$, then MH i defers transmission of its packet to a later time.

3 Adaptive Allocation Solution

The solution proposed in this paper is composed of two parts. The first part is performed once at the initialization of the Base Station (BS), while the second part is used at run time when the MHs are sending their streams of packets. Sections 3.1 and 3.2 describe these two phases in detail.

3.1 Initialization Phase

During the initialization phase, the BS computes a table of target SINRs. The table is indexed using three inputs: (i) an estimate of the number of transmissions of the packet possible prior to its deadline, (ii) an estimate of path loss $\mathcal{H}$ experienced by the MH's signal, and (iii) an estimate of the interference level $\mathcal{I}$ in the channel as seen by the MH. This table is used at run time to determine the optimal target SINR for each MH packet transmission. A method for computing the entries in this table is described below.

The method is based on a dynamic programming approach. More formally, we assume that a MH gets a reward $\Re$ if it correctly delivers a packet to the BS prior to its deadline. If the packet misses its deadline, the MH gets a reward of 0. The reward $\Re$ represents the positive impact on the QoS perceived by the application as a result of the packet being delivered to the destination on time. Since a packet that does not arrive on time is of no use to the receiver, we associate zero rewards for missed deadlines.

For each transmission using a target SINR $\gamma \in \Gamma$ we define a cost function $\mathcal{C}(\mathcal{H}, \mathcal{I}, \gamma)$ to model two factors: (i) the energy consumed in transmitting the packet to achieve a target SINR of γ, and (ii) the interference caused to other MHs as a result of transmitting at a power level required to achieve SINR of γ. For a MH, both these factors are a function of its path loss and the level of interference from other MHs. Specifically, we assume that the cost is

$$\mathcal{C}(\mathcal{H}, \mathcal{I}, \gamma) = \alpha P + \beta \gamma \tag{15}$$

where α and β are two design constants, P is the transmission power needed to achieve the requested target SINR γ. The first term in Equation (15) corresponds to the first factor and the second factor is included to model the adverse effect on other MHs. Note that, the larger the γ, the higher transmit power, and thus more interference for other MHs.

Observation 1: Consider the i^{th} mobile host having a packet ready for transmission at time t. Suppose that the deadline of the packet is such that at most one transmission is possible prior to its deadline. Also suppose that $\mathcal{H}_i$ and $\mathcal{I}_i$ are the estimated path loss and interference level for MH i during the transmission of the packet. Then, the expected net profit for MH if it uses a target SINR of $\gamma_i \in \Gamma$ is

$$\phi(\gamma_i, \mathcal{H}_i, \mathcal{I}_i, 1) = \eta \cdot \Re - \mathcal{C}(\mathcal{H}_i, \mathcal{I}_i, \gamma_i) \tag{16}$$

where $\eta = p(\mathcal{H}_i, \mathcal{I}_i, \gamma_i)$ is the probability of the packet being correctly transmitted over the wireless channel when the path loss and interference in the channel are $\mathcal{H}_i$ and $\mathcal{I}_i$

respectively, and the MH targets an SINR γ_i.

The justification for this observation is as follows. Since there is possibility for only one transmission, the delivery of the packet is successful only if the transmission resulted in correctable errors. When the wireless interface is in a state characterized by a path loss $\mathcal{H}_i$ and an interference $\mathcal{I}_i$, an SINR γ_i results in a correct transmission with probability $\eta = p\left(\mathcal{H}_i, \mathcal{I}_i, \gamma_i\right)$. Therefore, there is probability $\eta = p\left(\mathcal{H}_i, \mathcal{I}_i, \gamma_i\right)$ that the transmission results in a reward of $\Re$. Since the cost incurred by the MH in targeting an SINR of γ_i is $\mathcal{C}\left(\mathcal{H}_i, \mathcal{I}_i, \gamma_i\right)$, the expected net profit is as given by Equation(16). From this observation, the best possible SINR γ_i^* to target for the i^{th} MH's packet transmission is the one which maximizes the expected net profit, i.e.,

$$\gamma_i^* = \arg\max_{\gamma_i \in \Gamma} \phi\left(\gamma_i, \mathcal{H}_i, \mathcal{I}_i, 1\right). \tag{17}$$

Consequently, the optimal expected net profit is

$$\Phi\left(\mathcal{H}_i, \mathcal{I}_i, 1\right) = \max_{\gamma_i \in \Gamma} \phi\left(\gamma_i, \mathcal{H}_i, \mathcal{I}_i, 1\right). \tag{18}$$

Observation 2: Suppose the deadline of a packet is such that at most k transmissions are possible prior to its deadline. Also suppose that the the path loss in the channel for the i^{th} MH is $\mathcal{H}_i$ and the interference in the channel is $\mathcal{I}_i$. Then, the expected net profit for the packet, if the i^{th} MH targets an SINR of $\gamma_i \in \Gamma$, is

$$\phi\left(\gamma_i, \mathcal{H}_i, \mathcal{I}_i, k\right) = \eta \cdot \Re - \mathcal{C}\left(\mathcal{H}_i, \mathcal{I}_i, \gamma_i\right) + (1-\eta)\, \Phi\left(\overline{\mathcal{H}_i}, \overline{\mathcal{I}_i}, k-1\right) \tag{19}$$

The optimal target SINR to request for the transmission is

$$\gamma_i^* = \arg\max_{\gamma_i \in \Gamma} \phi\left(\gamma_i, \overline{\mathcal{H}_i}, \overline{\mathcal{I}_i}, k\right) \tag{20}$$

where $\overline{\mathcal{H}_i}$ and $\overline{\mathcal{I}_i}$ are the expected path loss and the expected interference, respectively, in the subsequent retransmissions of this packet. The justification for this observation is as follows. If the MH targets an SINR of γ_i for this transmission, then the transmission is successful with probability $p\left(\mathcal{H}_i, \mathcal{I}_i, \gamma_i\right)$. In that case, the MH is rewarded $\Re$. Otherwise, the transmission fails and the MH can retransmit the packet. At the time of the packet retransmission, the state of the wireless channel may be different resulting in a different path loss and a different interference level. In Equation(19) we use the expected values of the path loss $(\overline{\mathcal{H}_i})$ and the interference $(\overline{\mathcal{I}_i})$ for the subsequent retransmissions.

Path Loss $\mathcal{H}$	Interference Level $\mathcal{I}$	Num. of transmissions		
		1	2	3
High	$2\times N_o$	12.0	10.5	7.5
1e-18	$1000\times N_o$	8.5	8.5	8.0
	$6000\times N_o$	Defer	Defer	Defer
Medium	$2\times N_o$	12.0	10.5	7.5
1e-17	$1000\times N_o$	12.0	10.5	7.5
	$6000\times N_o$	11.0	11.0	7.5
Low	$2\times N_o$	12.0	10.5	7.5
1e-16	$1000\times N_o$	12.0	10.5	7.5
	$6000\times N_o$	12.0	10.5	7.5

Table 1: Example of Target SINR Table

From this observation, the optimal expected net profit, for the packet with k possible transmissions, when the wireless interface is characterized by a path loss $\mathcal{H}_i$ and an interference $\mathcal{I}_i$, can be obtained by recursively solving

$$\Phi\left(\mathcal{H}_i, \mathcal{I}_i, k\right) = \max_{\gamma_i \in \Gamma}\{\eta \cdot \Re - \mathcal{C}\left(\mathcal{H}_i, \mathcal{I}_i, \gamma_i\right) + (1-\eta)\Phi\left(\overline{\mathcal{H}_i}, \overline{\mathcal{I}_i}, k-1\right)\} \tag{21}$$

with $\Phi\left(\overline{\mathcal{H}}, \overline{\mathcal{I}}, 1\right)$ as given by Equation (18) for all $\overline{\mathcal{H}}$ and $\overline{\mathcal{I}}$ and $\eta = p\left(\mathcal{H}_i, \mathcal{I}_i, \gamma_i\right)$.

3.1.1 Numerical Example

In this section, we present an example of the target SINR table and give some intuition behind its entries. In this example, we assume that the path loss and interference levels for a MH can each be divided into three categories: high, medium, and low. We also assume that the set of possible target SINRs is $\Gamma = \{\text{defer}, 7, 7.5, 8, 8.5, 10.5, 11, 12\}$. The other parameters needed by the proposed algorithm are as follows: $G = 400$, $N_o = 5 \times 10^{-20}$, $\alpha = \beta = 0.1$, $\Re = 2000$, and packet size is 256 Bytes. Using these parameters and the equations developed in this section, we can calculate the entries shown in Table 1. In Table 1, we can observe a few trends. First, we notice that the targeted SINR decreases as the number of transmissions increases (going from left to right in the table). This means that a MH exploits the lack of urgency in delivering the packet to reduce its power consumption and produce less interference for other MHs. If, as a result of a smaller SINR the packet gets corrupted, the MH still has the time for more attempts using higher SINR. Second, note that, the third row in the table is all Defer. This means that if the path loss and the interference level are both high, the MH chooses to defer its transmission. This is because the cost of transmitting the packet in this case is very high relative to the potential reward for delivering the packet on time. Third, note that, for a given interference level and number of transmissions, the proposed scheme selects higher target SINR as the path loss decreases. This is because, for lower path loss, a higher SINR can be achieved with moderate powers, therefore reducing the cost of achieving the high SINR.

3.2 Run Time Phase

At run time, the BS periodically monitors the path loss $\mathcal{H}_i$ and the interference level $\mathcal{I}_i$ for each MH i. In the rest of this section, we assume that the BS always has a good estimate of the path loss and the interference for each MH in the cell.

Now suppose that the i^{th} MH has a packet ready for transmission at time t and that D is its deadline. Then, the following steps are executed in order to convey the packet to the BS.

Step 1: BS estimates the maximum number of retransmissions possible prior to the deadline of the packet as follows

$$maxTx = \left\lfloor \frac{D - t}{T} \right\rfloor \tag{22}$$

where T is the retransmission timeout period.

Step 2: If $maxTx \leq 0$ then the packet has either missed its deadline or it can not be transmitted prior to its deadline. In this case, the packet is dropped (The MH does not get the reward associated with the packet). The MH is advised to start transmitting a new packet.

Step 3: Using the value of the MH's path loss $\mathcal{H}_i$, the estimated interference $\mathcal{I}_i$, and $maxTx$ as indexes into the target SINR table, the BS obtains the optimal target SINR γ_i^* for the packet transmission.

Step 4: If $\gamma_i^* = \gamma^0$, then the MH is advised to defer transmission. Otherwise, the power needed to achieve the target SINR is conveyed to the MH.

Step 5: If the MH is not deferring, then the packet is transmitted using the power assigned by the BS.

Step 6: If the packet is transmitted in Step 5, set a timeout for a period T and wait for an acknowledgment from the BS. If the timeout expires prior to the receipt of an acknowledgment, go back to Step 1 to consider retransmission of the packet.

4 Simulation Model and Performance Measures

The evaluation is carried out using a simulation tool built in Matlab$^{\text{TM}}$. The simulator mimics a single CDMA wireless cell containing a number of MHs each having an infinite stream of real time data packets to transmit. The simulation starts with N mobile hosts uniformly distributed across the cell. During the course of the simulation, all MHs periodically move in randomly chosen directions.

The simulator implements a matched filter (MF) receiver and a minimum mean squared error (MMSE) receiver at each host. In addition, the simulator implements both the adaptive and the fixed schemes to select the target SINR for any given packet transmission. During the course of the simulation, all MHs deploy the same type of receiver (i.e. either the MF or the MMSE) and the same target SINR selection scheme (i.e. either fixed or adaptive). For each packet transmission, the fixed scheme uses a fixed target SINR for all MHs. However, in the adaptive scheme, the base station computes the target SINR for each MH transmission attempt as follows:

1. First, the path loss $\mathcal{H}_i$ is determined for each MH i by plugging its current position into Equation (23).
2. Second, the interference level $\mathcal{I}_i$ is computed based on the last transmissions of all active MHs. $\mathcal{I}_i$ is computed as given by Equations (4) for the MF receiver and (8) for the MMSE receiver.
3. Third, an integer maximum number of re-transmissions, maxTx, for each packet is selected from a uniform distribution, thus effectively selecting a deadline for each packet.
4. Finally, the base station determines the target SINR for each MH by indexing the SINR table using the parameters obtained in steps 1 through 3. The target SINR γ^* for the adaptive scheme is chosen from the set of values Γ described in Section 3.

Once the target SINRs are obtained for each MH, The base station uses the power control scheme, described in Section 2.3, to compute the adequate power level for each MH to use during the transmission of its next data packet.

4.1 Channel Model

The state of a wireless channel is usually characterized by the Bit-Error-Rate (BER) a MH observes during a packet transmission. The BER in turn is a function of the Signal to Interference and Noise Ratio (SINR) for a given MH. The SINR of a communication between a mobile host and a base station depends on two main factors: the path loss $\mathcal{H}$ and the interference $\mathcal{I}$. The path loss $\mathcal{H}$ depends on the distance between the mobile host and the base station, objects/obstructions in the paths between the host and the base station. The interference $\mathcal{I}$, however, depends on the relative locations and the powers of other nearby transmitters. Due to the path loss and interference, there is a considerable variation in the error rates observed in message packets transmitted over the wireless channel.

In this paper we assume that the path loss in the wireless channel is a random process. In our simulations, we use a model for the path loss in the channel developed by Erceg et. al [21]. This model was developed based on extensive experimental data collected in a large number of existing macro-cells in several suburban areas in New Jersey and around Seattle, Chicago, Atlanta, and Dallas. For more details on the collected data and the analysis, please refer to [21]. In this model the path loss $\mathcal{H}$ that a MH's signal experiences given that the MH is d meters away from the BS (for $d \geq d_o$) is written as follows:

$$\mathcal{H} = \left[20\log_{10}\left(\frac{4\pi d_o}{\lambda}\right) + 10\left(a - bh_b - \frac{c}{h_b}\right)\log_{10}\left(\frac{d}{d_o}\right)\right] + \left[10x\sigma_\gamma \log_{10}\left(\frac{d}{d_o}\right) + y\mu_\sigma + yz\sigma_\sigma\right] \tag{23}$$

where h_b is the BS antenna height in meters, λ is the carrier's wave length in meters, x, y, and z are independent zero-mean Gaussian variables of unit standard deviation, N(0,1). Both x and z vary from cell to cell, while y varies from location to location within a cell. The other parameters are experimentally measured quantities that vary depending on the type of terrain. These values can be found in [21].

This model is chosen to mimic the situation that occurs in practice where due to fading and multipath, the channel characteristics varies rapidly. In the simulations, the exact values of the stochastic parameters of this variation are not known to the MH or to the BS. However, the BS can monitor the past variation in the channel for each MH (its path loss and the interference level it observes in the channel) and estimate the stochastic parameter values necessary to make the SINR selection in the adaptive approach. Clearly, there will be uncertainties in the parameter values estimated by the MH.

4.2 Network Model

Multiple MHs in a single cell are simulated. All MHs are assumed to have an infinite stream of packets to send to the BS. Each packet is assigned a deadline by which it must be delivered to the BS. If a packet misses its deadline, it is dropped by the MH. We assume that each packet contains the deadline requirements of the next packet in the MH's queue.

In our simulator, the BS can run either the proposed adaptive scheme or a fixed scheme for picking the target SINRs. In the fixed scheme, each MH has a fixed target SINR. In the adaptive scheme, the BS generates a target SINR table during the initialization phase. The table is then used to determine the optimal target SINR for each MH at every transmission based on the path loss and the interference level measured at the BS. The BS then computes the transmit powers for each MH using the power control scheme described in Subsection 2.3.

The MHs transmit a packet using the power level determined by the BS. During the transmission, the path loss and the interference level for each MH are measured at the BS. The resulting average SINR is also computed for each MH. Using the SINR values, the average bit error rate and the corresponding packet error probability are computed. Each packet is randomly determined to be either correct or in error based on the corresponding computed packet error probability.

4.3 Simulation Parameters

The wireless channel path loss, $\mathcal{H}$, for each MH is determined by Equation (23). $\mathcal{H}$ depends on several parameters such as the frequency of operation, the base station antenna height and the type of terrain. In the results presented in this section, the frequency of operation is selected to be 1.9 GHz and the BS antenna height is chosen to be $h_b = 50$ meters. The terrain was assumed to be either hilly with light tree density or flat with moderate-to-heavy tree density. Specifically, $d_o = 100$ meters, $d_{max} = 2000$ meters, $a = 4.0$, $b = 0.0065$, $c = 17.1$, $\sigma_\gamma = 0.75$, $\mu_\sigma = 9.6$, and $\sigma_\sigma = 3.0$. The wireless channel processing gain G is selected to be 200 for the MMSE receiver and 20 for the MF receiver. The Gaussian noise in the channel is characterized by the value $\sigma^2 = 10^{-13}$.

For each MH's packet transmission a target SINR γ^* is picked. In the case of the fixed target SINR scheme, all MHs target 10 dBs ($\gamma^* = 10dB$) for each transmission attempt. However, in the adaptive scheme γ^* is selected from the set $\Gamma = \{0, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10.5, 11, 11.5, 12\}$ using the lookup table developed during the off line phase. In the set Γ,"0" represents deferment. That is if $\gamma^* = 0$ then the MH does not attempt to send its packet during the current transmission opportunity. To obtain the SINR lookup table the following parameters are used: $\alpha = \beta = 0.1$, and $\Re = 2000$.

Each data packet carries 256 bytes of data. A simulation run is terminated when all performance measure parameters converge within 10% of the real value with 95% confidence. In each run, the Gaussian random variables x and z that characterize a cell are chosen. Each run is repeated 20 times with different values for the random variables x and z to simulate different cells in the network. The results reported in this section is averaged over all cells.

4.4 Performance Measures

In this section, we present the performance measures that used evaluate the adaptive SINR selection scheme and compare it with the fixed scheme. Specifically we define two metrics namely the average power used per successful packet transmission and the network capacity.

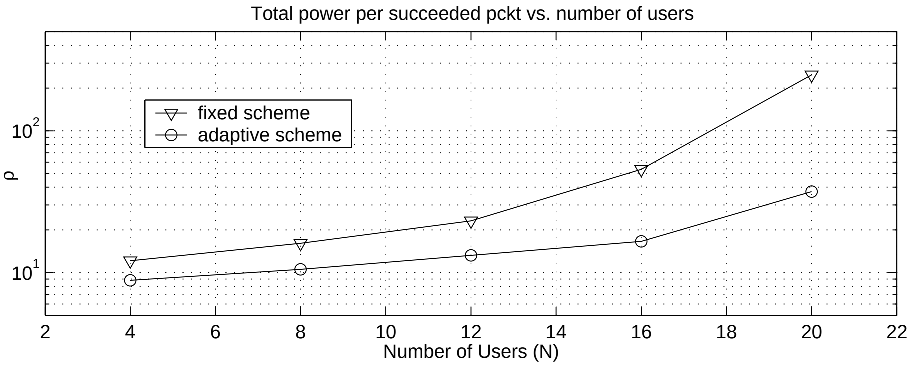
1. Average Power per Successful Transmission ρ: The simulator maintains the sum τ_i of the transmit powers over all transmissions for each MH i. The average power per successful transmission ρ is then obtained by dividing this sum by the total number M_i of packets delivered successfully by MH i during the course of the simulation. Specifically:

$$\rho = \frac{\sum_{i=1}^{N} \tau_i}{\sum_{i=1}^{N} M_i} \tag{24}$$

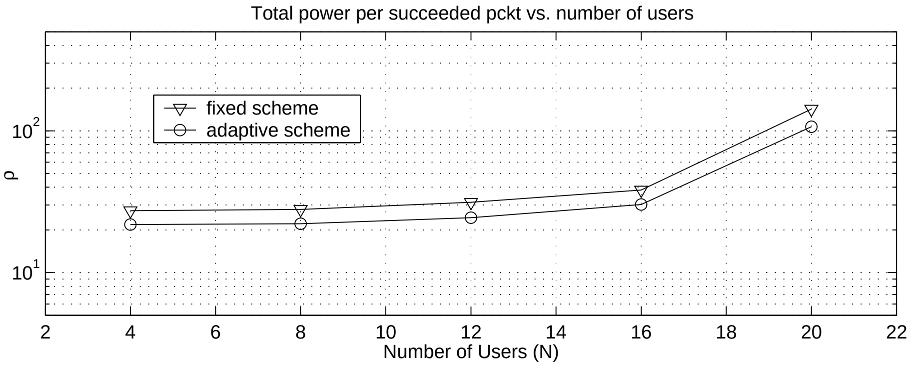
2. Network Capacity η: The network capacity is defined to be the maximum number of mobile hosts that can be supported in the network while satisfying their quality of service requirements. We define the QoS requirement for each mobile host in terms of a minimum required packet delivery success rate. The packet success rate is the fraction of packets that are correctly delivered to the BS prior to expiration of their deadlines.

5 Simulation Results

In this section, we evaluate the effectiveness of adaptively selecting the target signal to interference and noise ratio (SINR) and compare its performance to that of a statically assigned SINR.



(a) MF



(b) MMSE

Figure 2: Power Usage Comparison

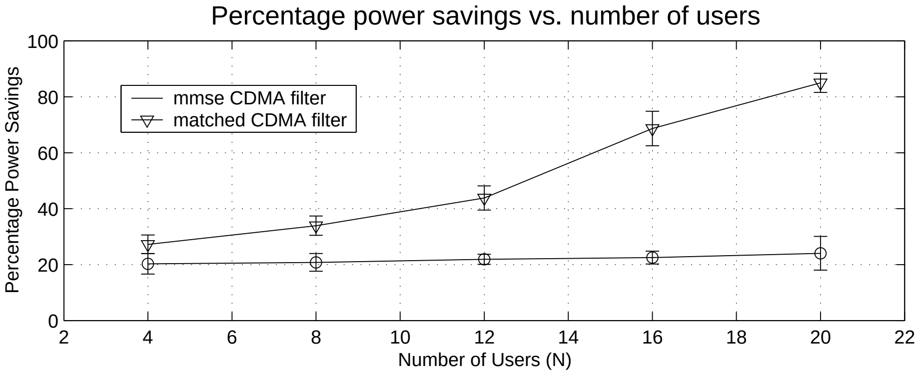


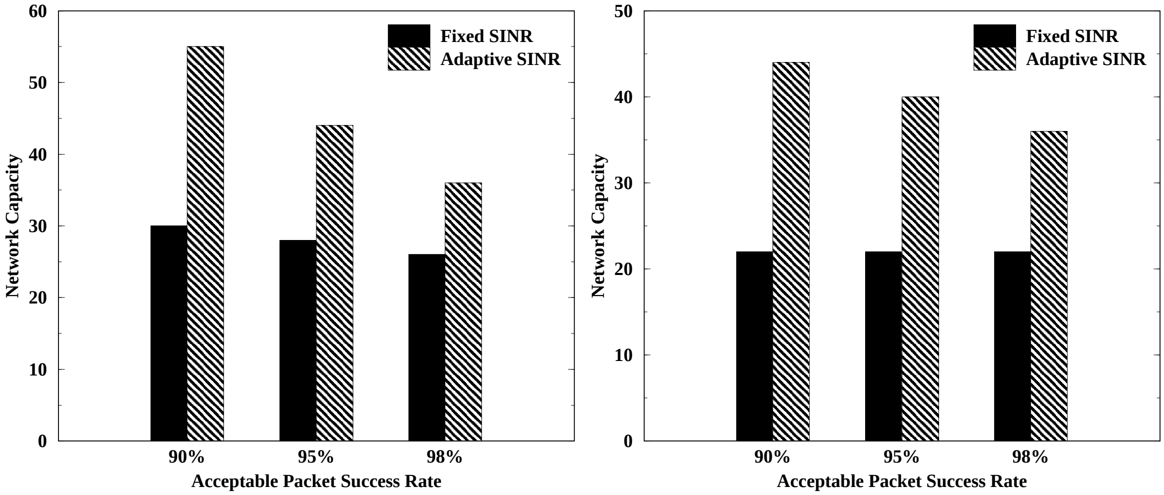
Figure 3: Percentage Power Savings

5.1 Power Savings

Figure 2 shows the average power used per successful transmission for the fixed SINR and the adaptive SINR selection schemes. The figure shows that our adaptive approach outperforms the fixed approach in terms of power usage. The corresponding percentage of Power Savings is shown in Figure 3. The results show that the adaptive scheme saves up to 80% of the total power in the MF receiver and up to 30% in the MMSE receiver. The reduction in power use per successful transmission can be explained as follows. Equations (4) and (8) show the dependence of the interference level $\mathcal{I}_i$ seen by MH i on the transmission power used by neighboring MHs. As the transmit power of neighboring hosts increases, the interference experienced by a MH increases. Note that the same effect is observed if the number of neighboring hosts increases. That is, when the number of MHs N increases in the network, the interference level $\mathcal{I}_i$ experienced by each MH i increases as well. Since in the fixed SINR case, each MH is always targeting the same SINR, to compensate for the higher interference, each MH must augment its transmit power in order to meet its targeted SINR (see Equation (1)). Furthermore, this increase in power causes the interference level to increase which in turn pushes the MHs to further increase their power.

The adaptive SINR selection scheme overcomes this "shouting" phenomenon. Specifically, during high interference periods, MHs often elect to either defer transmission to a later time or target smaller SINR if the deadline of the packet at the head of the queue permits. This effectively reduces the interference experienced by active hosts which in turn reduces their transmit powers.

Figure 3 shows that the power savings are less significant for the MMSE receiver. The reason for this is as follows. Equation (4) shows that for the MF receiver the interference observed by a MH i is a proportional to the sum of the powers of all neighboring hosts.



(a) MF

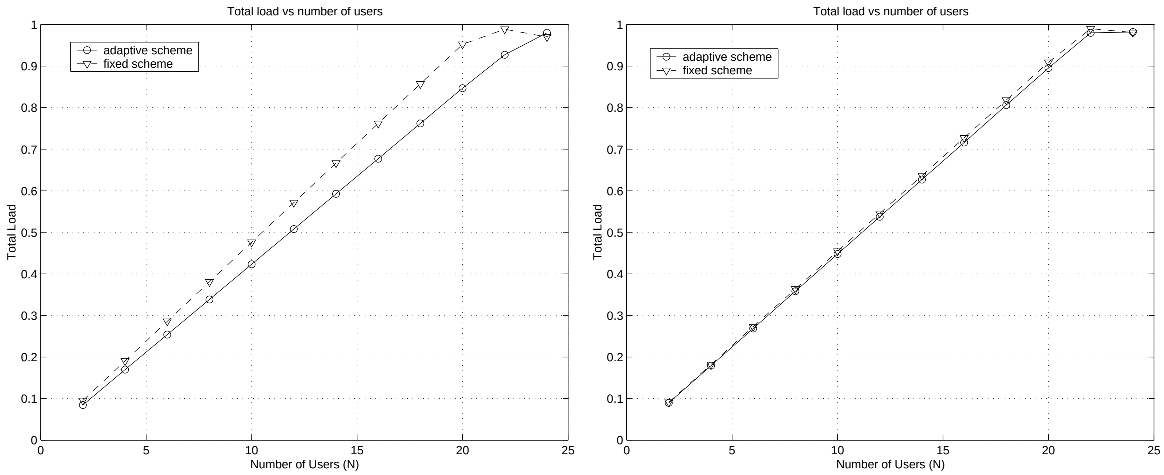
(b) MMSE

Figure 4: Network Capacity Comparison

However in the case of the MMSE receiver, Equation (8) shows that the interference observed by a MH i is a weaker function of the powers of neighboring hosts. Equation (8) shows that the MMSE receiver takes the spreading codes of all interfering neighboring hosts into account in the filtering of a MH's signal. Therefore, the MMSE receiver provides a better interference suppression capability than the MF receiver. Hence an increase in the number of MHs will only require a less significant increase in power for each MH to achieve its targeted SINR. This makes the "shouting" phenomenon less pronounced in the MMSE receiver case than the MF case.

5.2 Network Capacity

Figure 4 compares the network capacity between the fixed and the adaptive SINR selection schemes for both the MF and the MMSE type receivers. The capacity is shown for three thresholds of acceptable packet success rates: 90%, 95% and 98%. The justification for the selection of these packet success rates is as follows. Typical voice traffic using the G711 codec for example can tolerate up to 2% packet loss (packet success rate higher or equal to 98%) and still maintain acceptable quality [22]. Whereas based on results derived by Mathis et al. in [23], TCP can sustain up to 10% packet loss while achieving acceptable throughput. Thus the selection of 90% and 95% packet success rates (or equivalently 10% 5% packet loss respectively).



(a) MF

(b) MMSE

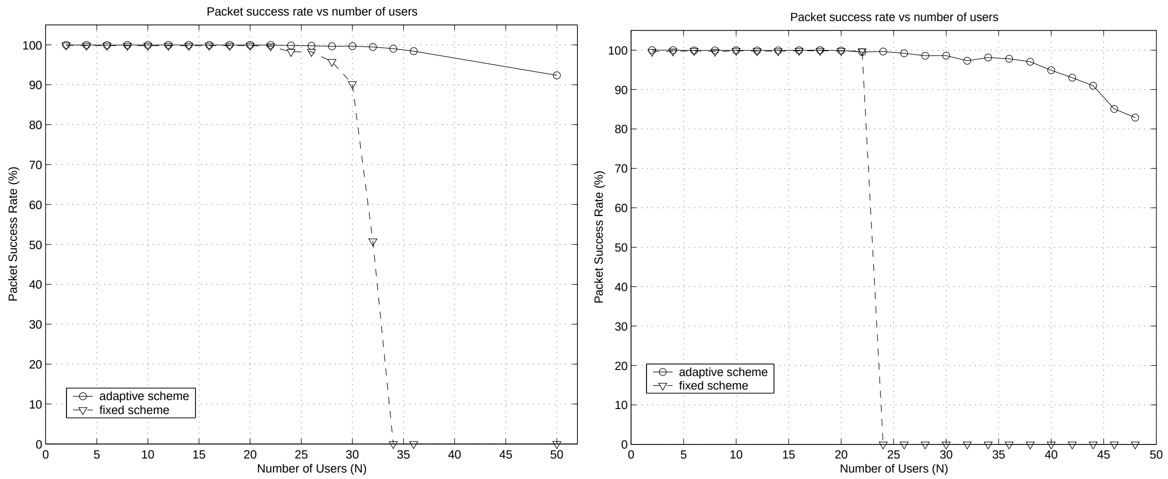
Figure 5: Network Load ($\mathcal{L}$)

Figure 4 shows that the adaptive scheme enhances the capacity of the network at each of the acceptable packet success rates. Specifically, the adaptive scheme achieves an increase in capacity between 38% and 83% over the fixed SINR selection scheme when a MF receiver is used and an increase in capacity between 64% and 100% when an MMSE receiver is used. In the rest of this section we analyze and present the reasons behind these large increases in capacity.

Figure 5 shows the network load as a function of the number of users N in the network for the fixed and the adaptive SINR selection schemes. Figure 5(a) shows the network load for the MF receiver while Figure 5(b) shows the network load for the MMSE receiver. Figure 6 shows a comparison of the packet success rates for both the fixed and adaptive schemes for both the MF and the MMSE receivers.

When the network load is smaller than 1, we observe that the packet success rate is very close to 100% for both the fixed and adaptive schemes. We also note that this is true independent of the receiver. The reason for this is as follows. Up to 22 users, the network is not saturated ($\mathcal{L} < 1$). In this case, the power control scheme, for both receivers, achieves the target SINRs of all MHs most of the time. Moreover, the fixed target SINR is large enough to guarantee correct packet delivery with high success probability. Likewise, the set of SINRs from which the BS selects the adaptive targets contains values assuring correct delivery with high success probability as well.

However, when the network load is greater than 1 (i.e., when the number of MHs



(a) MF

(b) MMSE

Figure 6: Packet Success Rate

exceeds 22), there is no feasible power vector to satisfy the targeted fixed SINRs for all users. The power control scheme reverts to scaling back the target SINRs so that a power vector solution is feasible (see discussion in Section 2.3). As mentioned in Section 2.1, the packet success rate is a function of the SINR. Figure 1 shows that at a certain value of the SINR $\overline{\gamma}$ (around 6 dBs), the packet success function switches suddenly from high value to low value. Thus, a slight variation in the SINR, around $\overline{\gamma}$, results in a dramatic change in the packet success rate. Now, since the fixed scheme targets fixed SINRs for all MHs then when the network becomes loaded, the power control scheme scales down all SINRs equally. Therefore, there is a threshold number of MHs at which all the SINRs fall below $\overline{\gamma}$ resulting in a sudden drop of the packet success rate of all MHs. Results in Figure 6 show that the rapid drop of the packet success rate occurs when the fixed scheme is used and independently of the receiver.

However, in the adaptive SINR selection scheme, MHs do not always target high SINRs. Whenever their deadlines permit they select a smaller target SINR or defer all together. In this case the power control scheme is able, most of the time, to find a feasible solution to satisfy all simultaneously active MHs. While the SINRs of some MHs drop below $\overline{\gamma}$, those of others remain high resulting only in a small drop of the packet success rate. This results in a smaller network load and an increase of the network capacity (number of MHs that can be serviced simultaneously by the network).

Therefore, because of the adaptation, our scheme increases the capacity of the network while assuring higher packet success rate for all MHs.

6 Conclusion

In this paper, we proposed an adaptive allocation scheme that dynamically assigns Signal to Interference and Noise Ratios (SINRs) to the Mobile Hosts (MHs) in a CDMA network. The objective of our scheme is to guarantee the Quality of Service (QoS) requirements of all the MHs while increasing the capacity of the network and decreasing the amount of power used by the MHs to transmit their packets to the Base Station (BS). For each transmission, this goal is achieved by (*i*) carefully deferring transmission of packets of MHs whenever their deadlines permit and the channel is relatively noisy, and (*ii*) adaptively selecting the SINRs that optimize the profit functions of MHs. We compared and evaluated the performance of the adaptive approach to that of a traditional static approach by means of simulations. We showed that the adaptive allocation scheme saves up to 80% for the Matched Filter (MF) receiver and 30% for the Minimum Mean Squared Error (MMSE) receiver of the total power used by MHs as opposed to the static scheme. In addition, we showed that our proposed scheme increases the capacity of the network significantly while satisfying the QoS requirements of MHs. In fact, we demonstrated that the adaptation technique permits the network to service up to 45 MHs with a packet success rate higher than 90% for all MHs whereas the fixed approach service only up to 30 MHs at the same success rate.

References

[1] M. Xiao, N. B. Shroff, and E. K. P. Chong, "Utility-based power control in cellular wireless systems," in *IEEE Infocom*, vol. 1, pp. 412–421, 2001.

[2] J. Li, N. Shroff, and E. Chong, "A static control scheme for wireless cellular networks," in *IEEE Infocom*, vol. 2, pp. 932–939, March 1999.

[3] C. Huang and R. Yates, "Rate of convergence for minimum power assignment algorithms in cellular radio systems," *Wireless Networks*, vol. 4, no. 3, pp. 223–231, 1998.

[4] R. Yates and C. Huang, "Integrated power control and base station assignment," *IEEE Transaction on Vehicular Technology*, vol. 44, pp. 638–644, November 1993.

[5] S. Grandhi, R. Vijayan, D. Goodman, and J. Zander, "Centralized power control in cellular radio systems," *Transaction on Vehicular Technology*, vol. 42, pp. 466–468, November 1993.

[6] R. Yates, "A framework for uplink power control in cellular radio systems," *IEEE Journal on Selected Areas of Communications*, vol. 13, pp. 1341–1348, September 1995.

[7] J. Zander, "Performance of optimum transmitter power control in cellular radio systems," *IEEE Transactions on Vehicular Technology*, vol. 41, pp. 57–62, Febreray 1992.

[8] K. Leung, "A kalman-filter method for power control in broadband wireless networks," in *IEEE Infocom*, vol. 2, pp. 948–956, March 1999.

[9] A. Yener, C. Rose, and R. Yates, "Optimum power scheduling for CDMA access channels," in *IEEE Global Telecommunications Conference*, pp. 1499–1503, 1997.

[10] S. Ariyavisitakul and L. Chang, "Signal and interference statistics of a CDMA systems with feedback power control," *IEEE Transactions on Communications*, vol. 41, pp. 1626–1634, November 1993.

[11] S. Ariyavisitakul, "Signal and interference statistics of a CDMA systems with feedback power control - part II," *IEEE Transactions on Communications*, vol. 42, pp. 597–605, April 1994.

[12] V. Shah, N. Mandayam, and D. Goodman, *Power control for wireless data based on utility and pricing.* Technical report, WINLAB-TR-159, 1998.

[13] G. Foschini and Z. Miljanic, "A simple distributed autonomous power control algorithm and its convergence," *IEEE Transaction on Vehicular Technology*, vol. 42, pp. 641–646, November 1993.

[14] A. Sampath, P. Kumar, and J. Holtzman, "Power control and resource management for a multimedia CDMA wireless system," in *IEEE sixth International Symposium on Personal, Indoor and Mobile Communications*, vol. 1, pp. 21–25, September 1995.

[15] S. Grandhi, R. Vijayan, and D. Goodman, "Distributed power control in cellular radio systems," *IEEE Transactions on Communications*, vol. 42, pp. 226–228, April 1994.

[16] S. Ulukus and R. Yates, "Adaptive power control and MMSE interference suppression," *Wireless Networks*, vol. 4, no. 6, pp. 489–496, 1998.

[17] S. Ulukus and R. Yates, "Stochastic power control for cellular radio systems," *IEEE Transactions on Communications*, vol. 46, pp. 784–798, June 1998.

[18] S. V. Hanly and D. N. Tse, "Power control and capacity of spread spectrum wireless networks," *Automativa*, vol. 35, pp. 1987–2012, December 1999.

[19] M. Elaoud and P. Ramanathan, “Adaptive allocation of CDMA resources for network-level qos assurances,” in *ACM Mobicom*, pp. 191–199, August 2000.

[20] J. G. Proakis and M. Salehi, *Communication Systems Engineering.* Prentice Hall Inc., 1994.

[21] V. Erceg, L. J. Greenstein, S. Y. Tjandra, S. R. Parkoff, A. Gupta, B. Kulic, A. A. Julius, and R. Bianchi, “An emperically based path loss model for wireless channels in suburban environments,” *IEEE Journal on Selected Areas of Communications*, vol. 17, pp. 1205–1211, July 1999.

[22] E. T. . .-. V2.1.1, *ITU-T Recommendation P.59 Conversational Voice.* ETSI, 1993.

[23] J. M. M. Mathis, J. Semke and T. Ott, “The macroscopic behavior of the tcp congestion avoidance algorithm,” *ACM’s Computer Communication Review*, July 1997.