

Minimum Average Transmission Power Routing in CDMA Ad Hoc Networks Utilizing the Blind Multiuser Detection

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Abstract

An ad hoc network is a self-organized and distributed entity, consisting of a number of mobile stations (MSs) without the coordination of any centralized access point. In this context, we discuss how to minimize the average transmission power in CDMA (Code Division Multiple Access) ad hoc networks for real-time service and data service utilizing the multiuser detection technique. Jointly considering the multiuser interference, coding scheme, and different service requirements, the Minimum Average Transmission Power Routing (MATPR) for both real-time service and data service have been proposed to minimize the average transmission power. Both theoretical analysis and simulation results indicate the advantages of the proposed routing method in the sense of power saving.

1 Introduction

An ad hoc network [1, 2, 3, 4] is a distributed system consisting of many mobile stations (MSs) with no predetermined topology and central control. The MSs in an ad hoc network communicate wirelessly in a self-organized manner. Such networks can be used in situations where either there is no other wireless communication infrastructure present or where such infrastructure cannot be used. A CDMA ad hoc network outperforms a TDMA ad hoc network in many respects. In this paper, we consider the CDMA ad hoc networks, in which each MS will obtain its signature sequence (orthogonal spreading code) to transmit the data. In such networks, the blind or group blind multiuser detection techniques [5, 6, 7] should be used. MSs typically operate on battery, which means the utilizable power for each MS is extremely constrained. Hence how to minimize the average transmission power is very important. This context is concerned with the utilization of the recent

blind multiuser detection techniques to minimize the average transmission power in CDMA ad hoc networks. Some power-saving schemes have been proposed for ad hoc networks [3, 4]. However, existing power-saving algorithms have not take into account the service requirements and the link quality, which indeed are very important for the performance. In this paper, we propose the Minimum Average Transmission Power Routing (MATPR) for both real-time service and data service to minimize the average transmission power, which jointly considers multiuser interference, coding scheme, and different service requirements.

The rest of this paper is organized as follows. The blind multiuser detection will be described in Section 2, and in Section 3, we will propose the MATPR in multihop ad hoc networks for both real-time service and data service. The simulation results will be shown in Section 4. Finally we conclude in Section 5.

2 Multiuser Detection

2.1 Synchronous CDMA Signal Model

We start by introducing the most basic multiple-access signal model, namely, a baseband, G -user, time-invariant, synchronous, additive white Gaussian noise (AWGN) system, employing periodic (short) spreading sequences, and operating with a coherent BPSK modulation format. The continuous-time waveform received by a given user in such a system can be modeled as follows

$$r(t) = \sum_{k=1}^G \sqrt{P_k} \sum_{i=0}^{M-1} b_k[i] s_k(t - iT) + n(t), \quad (1)$$

where M is the number of data symbols per user in the data frame of interest; T is the symbol interval; P_k , $\{b_k[i]\}_{i=0}^{M-1}$ and $s_k(t)$ denote respectively the power level, the transmitted symbol stream, and the normalized signaling waveform

of the k -th user; and $n(t)$ is the baseband white Gaussian ambient channel noise with power spectral density σ^2 . It is assumed that for each user k , $\{b_k[i]\}_{i=0}^{M-1}$ is a collection of independent equiprobable ± 1 random variables, and the symbol streams of different users are independent. The user signaling waveform is of the form

$$s_k(t) = \frac{1}{\sqrt{N}} \sum_{j=0}^{N-1} c_{j,k} \psi(t - jT_c), \quad 0 \leq t < T, \quad (2)$$

where N is the processing gain; $\{c_{j,k}\}_{j=0}^{N-1}$ is a signature sequence of ± 1 's assigned to the k -th user; and $\psi(\cdot)$ is a chip waveform of duration $T_c = \frac{T}{N}$ and with unit energy, i.e., $\int_0^{T_c} \psi(t)^2 dt = 1$.

At the receiver, the received signal $r(t)$ is filtered by a chip-matched filter and then sampled at the chip rate. The sample corresponds to the j -th chip of the i -th symbol is given by

$$r_j[i] \triangleq \int_{iT+jT_c}^{iT+(j+1)T_c} r(t) \psi(t - iT - jT_c) dt, \quad j = 0, \dots, N-1; \quad i = 0, \dots, M-1. \quad (3)$$

The resulting discrete-time signal corresponding to the i -th symbol is then given by

$$\mathbf{r}[i] = \sum_{k=1}^G \sqrt{P_k} b_k[i] \mathbf{s}_k + \mathbf{n}[i] = \mathbf{S} \sqrt{\mathbf{P}} \mathbf{b}[i] + \mathbf{n}[i], \quad (4)$$

with

$$\mathbf{r}[i] \triangleq [r_0[i] \ r_1[i] \ \dots \ r_{N-1}[i]], \quad (5)$$

$$\mathbf{s}_k \triangleq \frac{1}{\sqrt{N}} [c_{0,k} \ c_{1,k} \ \dots \ c_{N-1,k}], \quad (6)$$

$$\mathbf{n}[i] \triangleq [n_0[i] \ n_1[i] \ \dots \ n_{N-1}[i]], \quad (7)$$

where $n_j[i] = \int_{iT+jT_c}^{(j+1)T_c} n(t) \psi(t - iT - jT_c) dt \sim \mathcal{N}(0, \sigma^2)$

is a Gaussian random variable; $\mathbf{n}[i] \sim \mathcal{N}(\mathbf{0}, \sigma^2 \mathbf{I}_N)$; $\mathbf{S} \triangleq [\mathbf{s}_1 \ \dots \ \mathbf{s}_G]$; $\mathbf{P} \triangleq \text{diag}(P_1, \dots, P_G)$; and $\mathbf{b}[i] \triangleq [b_1[i] \ \dots \ b_G[i]]^T$.

2.2 Multi-User Detector

Suppose that we are interested in demodulating the data bits of a particular user, say user 1, $\{b_1[i]\}_{i=0}^{M-1}$, based on the received waveforms $\{\mathbf{r}[i]\}_{i=0}^{M-1}$. A linear receiver for this purpose is a vector $\mathbf{w}_1 \in \mathbb{R}^N$, such that the desired user's data bits are demodulated according to

$$z_1[i] = \mathbf{w}_1^T \mathbf{r}[i], \quad (8)$$

$$\hat{b}_1[i] = \text{sign}\{z_1[i]\}. \quad (9)$$

Substituting (4) into (8), the output of the linear receiver \mathbf{w}_1 can be written as

$$z_1[i] = \sqrt{P_1} (\mathbf{w}_1^T \mathbf{s}_1) b_1[i] + \sum_{k=2}^G \sqrt{P_k} (\mathbf{w}_1^T \mathbf{s}_k) b_k[i] + \mathbf{w}_1^T \mathbf{n}[i]. \quad (10)$$

In (10), the first term contains the useful signal of the desired user; the second term contains the signals from other undesired users – the so-called *multiple-access interference* (MAI); and the last term contains the ambient Gaussian noise. The linear minimum mean-square error (MMSE) detector is designed to minimize the total effect of the MAI and the ambient noise at the detector output. Specifically, it is given by the solution to the following optimization problem

$$\mathbf{w}_1 = \arg \min_{\mathbf{w} \in \mathbb{R}^N} E \left\{ (b_1[i] - \mathbf{w}^T \mathbf{r}[i])^2 \right\} = \mathbf{C}_r^{-1} \mathbf{s}_1, \quad (11)$$

with

$$\begin{aligned} \mathbf{C}_r &\triangleq E \{ \mathbf{r}[i] \mathbf{r}[i]^T \} = \sum_{k=1}^G P_k \mathbf{s}_k \mathbf{s}_k^T + \sigma^2 \mathbf{I}_N \\ &= \mathbf{S} \mathbf{P} \mathbf{S}^T + \sigma^2 \mathbf{I}_N. \end{aligned} \quad (12)$$

It is seen from (12) that the linear MMSE detector \mathbf{w}_1 is a function of the signature sequences \mathbf{S} of all G users. Recall that for the matched-filter receiver, the only prior knowledge required is the desired user's signature sequence \mathbf{s}_1 . If the receiver only has the knowledge of its own signature sequence, but not of other users, the problem of *blind* implementation of the linear detector should be addressed, i.e., without the requirement of knowing the signature sequences of the interfering users.

Let the eigendecomposition of \mathbf{C}_r in (12) be

$$\mathbf{C}_r = \mathbf{U}_s \mathbf{\Lambda}_s \mathbf{U}_s^T + \sigma^2 \mathbf{U}_n \mathbf{U}_n^T, \quad (13)$$

where $\mathbf{\Lambda}_s = \text{diag}(\lambda_1, \dots, \lambda_G)$ contains the largest G eigenvalues of \mathbf{C}_r ; $\mathbf{U}_s = [\mathbf{u}_1, \dots, \mathbf{u}_G]$ contains the eigenvectors corresponding to the largest G eigenvalues in $\mathbf{\Lambda}_s$; $\mathbf{U}_n = [\mathbf{u}_{G+1}, \dots, \mathbf{u}_N]$ contains the $(N - G)$ eigenvectors corresponding to the smallest eigenvalue σ^2 of \mathbf{C}_r . It is known that $\text{range}(\mathbf{U}_s) = \text{range}(\mathbf{S})$ is the signal subspace; and $\text{range}(\mathbf{U}_n) \perp \text{range}(\mathbf{S})$ is the noise subspace. The linear MMSE detector \mathbf{w}_1 in (11) can also be written in terms of the signal subspace components as [6]

$$\mathbf{w}_1 = \mathbf{U}_s \mathbf{\Lambda}_s^{-1} \mathbf{U}_s^T \mathbf{s}_1. \quad (14)$$

Corresponding to the two forms of the linear MMSE detector (11) and (14), there are two approaches to its blind implementation. In the direct-matrix-inversion (DMI) method,

the autocorrelation matrix C_r in (11) is replaced by the corresponding sample estimate. That is

$$\hat{C}_r = \frac{1}{M} \sum_{i=1}^M \mathbf{r}[i] \mathbf{r}[i]^T, \quad (15)$$

$$\hat{\mathbf{w}}_1 = \hat{C}_r^{-1} \mathbf{s}_1. \quad [\text{DMI blind linear MMSE detector}] \quad (16)$$

In the subspace method, the eigencomponents \mathbf{A}_s and \mathbf{U}_s in (14) are replaced by the corresponding eigenvalues and eigenvectors of the sample autocorrelation matrix \hat{C}_r . That is

$$\begin{aligned} \hat{C}_r &= \frac{1}{M} \sum_{i=1}^M \mathbf{r}[i] \mathbf{r}[i]^T \\ &= \hat{\mathbf{U}}_s \hat{\mathbf{\Lambda}}_s \hat{\mathbf{U}}_s^T + \hat{\mathbf{U}}_n \hat{\mathbf{\Lambda}}_n \hat{\mathbf{U}}_n^T, \end{aligned} \quad (17)$$

$$\hat{\mathbf{w}}_1 = \hat{\mathbf{U}}_s \hat{\mathbf{\Lambda}}_s \hat{\mathbf{U}}_s^T \mathbf{s}_1, \quad [\text{Subspace blind linear MMSE}] \quad (18)$$

where $\hat{\mathbf{\Lambda}}_s$ and $\hat{\mathbf{U}}_s$ contain respectively the largest G eigenvalues and the corresponding eigenvectors of \hat{C}_r ; $\hat{\mathbf{\Lambda}}_n$ and $\hat{\mathbf{U}}_n$ contain respectively the remaining eigenvalues and eigenvectors of C_r .

According to [7], the output SINR of the blind detector can be expressed as

$$\begin{aligned} \text{SINR}_1 &= P_1 (\mathbf{w}_1^T \mathbf{s}_1)^2 / \left(\sum_{k=2}^G P_k (\mathbf{w}_1^T \mathbf{s}_k)^2 + \right. \\ &\quad \left. \sigma^2 \|\mathbf{w}_1\|^2 + \frac{1}{M} [(G+1) \mathbf{w}_1^T \mathbf{s}_1 \right. \\ &\quad \left. - 2 \sum_{k=1}^G P_k^2 (\mathbf{w}_1^T \mathbf{s}_k)^2 \mathbf{w}_k^T \mathbf{s}_k + (N-G) \tau \sigma^2] \right), \end{aligned} \quad (19)$$

where $\mathbf{w}_l^T \mathbf{s}_k$ and $\|\mathbf{w}_1\|^2$ are given respectively by

$$\mathbf{w}_l^T \mathbf{s}_k = \frac{1}{P_l} [\mathbf{R}(\mathbf{R} + \sigma^2 \mathbf{P}^{-1})^{-1}]_{k,l}, \quad k, l = 1, \dots, G, \quad (20)$$

$$\|\mathbf{w}_1\|^2 = \frac{1}{P_1^2} [(\mathbf{R} + \sigma^2 \mathbf{P}^{-1})^{-1} \mathbf{R}(\mathbf{R} + \sigma^2 \mathbf{P}^{-1})^{-1}]_{1,1} \quad (21)$$

, and

$$\tau \sigma^2 = \begin{cases} \mathbf{w}_1^T \mathbf{s}_1, & [\text{DMI}] \\ \frac{\sigma^4}{P_1^2} [(\mathbf{R} + \sigma^2 \mathbf{P}^{-1})^{-1} \mathbf{P}^{-1} \mathbf{R}^{-1}]_{1,1}, & [\text{Subspace}] \end{cases}$$

Note that the last term in the denominator of (19) represents the noise power due to the estimation error. Also note that the performance difference between the two forms of blind

detectors is due to the term τ . It is shown in [7] that in realistic channels the subspace blind detector outperforms the DMI blind detector. It is also shown there that the output of the blind detector is approximately Gaussian. Therefore the BER can be expressed as

$$P_{b,1} = Q\left(\sqrt{\text{SINR}_1}\right). \quad (22)$$

3 Proposed Minimum Average Transmission Power Routing (MATPR)

The considered network is a CDMA ad hoc networks consisting of a number of MSs, and each MS is assigned a signature sequence (orthogonal spreading code). Assume the length of the data packet is L , and the block coding scheme is applied for the data packet with the error-correction capability as t . In a CDMA ad hoc network, due to the limited transmission power of the MSs, the packets may be relayed over multiple MSs until the destination MS is reached. Hence the routing protocol should be provided, which is one of central issues for such networks. Since MSs typically operate on battery, the routing methods should have good power-saving property. Given a source MS and a destination MS, we are interested in the problem how to discover the route from the source to the destination which can minimize the average packet transmission power in CDMA ad hoc networks. Assume the power of each MS is fixed and can not be adjusted. For an MS i , denote P_i as its transmission power. Moreover, since compared with the transmission power, the receiving power can be negligible, we only consider the transmission power. The problem should be discussed under different types of service.

3.1 Channel Requirements for Different Types of Service

3.1.1 Normal Data Service

For the normal data service, typically there is no requirement on the packet transmission latency from the source to the destination. However, the required Bit Error Rate (BER) is pretty low such as 10^{-8} . For wireless mobile communications, even in CDMA systems, it is difficult to achieve such BER requirement. Hence, from the physical layer, error-correction coding schemes such as BCH codes are utilized to correct errorly transmitted bits, and from the Media Access Control (MAC) layer, acknowledgment scheme is adopted to guarantee the correct reception. We assume the block code with the error-correction capability as t is applied for the data packets. The basic acknowledgment procedure is briefly described as follows. Suppose A transmits one packet to B , and B detects the packet errorly received,

and can not correct the errors (note that the error correction capability of the BCH codes is limited). B will transmit an Error-Received message to A , and A will retransmit the packet to B . If B correctly receives the packet, it will transmit an Correct-Received message to A , and A will be aware of that. In the multihop packet transmission, along a certain route, we assume only after an intermediate MS receives the packet successfully from the preceding MS, it can transmit the packet to the next MS. For example, suppose the route is $S \rightarrow A \rightarrow B \rightarrow C \rightarrow D$. Assume S transmits a packet to A . Only after A successfully receives the packet, it will transfer the packet to B , which means the acknowledgment scheme is link-based. For the normal data service, we should jointly consider the coding scheme, acknowledgment scheme, multiuser interference to design the routing method which can minimize the average packet transmission power in CDMA ad hoc networks.

3.1.2 Real-time Service

For the real-time service, the packet transmission latency is strictly constrained while the required BER is not very low (for example, 10^{-2}). Hence, the packet retransmission can not be adopted. Any packet from the source should go through the route only once, and the errorly transmitted bits are solely corrected by the error-correction codes. Assume the required BER for the real-time service is P_{real} . For such service, we should first determine the conditions by which two MSs can directly communicate between each other to satisfy the real-time service requirements. Then the routing method should be proposed to minimize the average packet transmission power.

3.2 MATPR for the Normal Data Service

The blind detector is assumed to be installed on the receiver of each MS to demodulate the data packets.

3.2.1 Link Cost

Suppose MS i transmits the data to MS j directly, and j is aware of i 's signature sequence. Then the blind detector of j can obtain the SINR of data from i by (19). For the BPSK signal, the bit error rate P_b is given by (22). For one packet, due to the utilization of block codes, up to t errors in the packet can be corrected. Hence the packet error rate

$$P_e = \sum_{i=t+1}^L \binom{L}{i} P_b^i (1 - P_b)^{L-i}. \quad (23)$$

Since the transmission power of i is P_i , the average power consumption for transmitting one data packet from i can be represented as αP_i . α is a network parameter, which is dependent on the packet length, the bandwidth, etc. When

network is given, α can be determined. When the packet is errorly received (the number of error bits in the packet exceeds t), the acknowledgment scheme will require the packet to be re-transmitted until the packet is received successfully. Hence to transmit a data packet from i to j , the average transmission power consumption is

$$P_{average} = \alpha P_i \sum_{l=0}^{inf} P_e^l (1 - P_e)(l + 1) = \alpha P_i / (1 - P_e) \quad (24)$$

From the point view of the transmission power consumption, the cost of the link from i to j should be $\alpha P_i / (1 - P_e)$. Note that the link cost is directional, i.e., the cost of the link from i to j is different from the link cost from j to i .

After determining the link cost related with the average transmission power consumption, the routing method to minimize the average packet transmission power can be proposed. Existing routing schemes for ad hoc networks can be mainly divided into two groups: the reactive routing and the proactive routing. In the proactive routing scheme, each MS attempts to maintain its routing table so that the route can be utilized immediately when a packet needs to be forwarded. Reactive routing scheme, on the other hand, invokes a route discovery process only on-demand. No routing table is necessary to be maintained in each MS. Hence, when the network topology changes infrequently, the proactive routing scheme should be adopted. Otherwise we should adopt the reactive routing scheme. In this context, we describe two different versions of the MATPR.

3.2.2 Proactive MATPR

The basic procedure of the proactive MATPR is as follows. For an MS i , it should detect the average SINR of all its neighbors (assume each MS is aware of the signature sequences of its neighbors). The neighbor of an MS A means the MS of which the received power at A is not too weak (possible for demodulation). Moreover, based on modulation and coding scheme, the packet error rate of each link destined to A can be determined, and will be broadcasted periodically by A . Hence, each MS is aware of the packet error rate of each link started from the MS. By (24), each MS can calculate the cost of the link started from itself, and the local link cost table can be established to record the link cost. Periodically all MSs should broadcast its local link cost table to the network, and hence each MS can have the global link cost table. Considering the link cost > 0 , the Dijkstra Algorithm [8] can be utilized to obtain the minimum average transmission power route for each MS pair.

3.2.3 Reactive MATPR

The basic procedure of the reactive MATPR is as follows. For an MS i , it should detect the average SINR of all its

neighbors, and then calculate the packet error rate of each link destined to it. No information will be broadcasted. Suppose S attempts to discover a route to D . S should broadcast a route request packet which includes its transmission power and other routing information. Assume another MS A receives the packet, A will calculate the average transmission power cost utilizing A 's transmission power and the packet error rate for the corresponding link by (24). The determined link cost and the transmission power of A will be included in the packet, and then A will broadcast the modified route request packet again. The process will be repeated until the route request packet arrives at the destination MS D . D may receive multiple route request packets and it will choose the one which includes the minimum overall link costs as the selected route. Then D will reply a route reply packet to S including the selected route list. Finally S will obtain the reply packet, and the data communication can start over the selected route.

3.3 MATPR for the Real-time Service

The blind detector is assumed to be installed on the receiver of each MS to demodulate the data packets.

3.4 Link Determination

Suppose MS i transmits the real-time data to MS j directly, and j is aware of i 's signature sequence. Then the blind detector of j can obtain the SINR of data from i by (19). For the BPSK signal, the bit error rate P_b is given by (22). Since the packet length is L , and up to t errors can be corrected, if $P_{real} \geq P_b - \frac{t}{L}$, the link from i to j is assumed to be reliable for real-time data transmission. Otherwise, the real-time data can not be reliably transmitted from i to j . Thus, if a link exists for real-time service, the corresponding bit error rate of the link $P_b \leq P_{real} + \frac{t}{L}$. By (22), we have the following link determination condition: for a link from A to B , at B 's receiver, if

$$Q\left(\sqrt{SINR_1}\right) \leq P_{real} + \frac{t}{L}, \quad (25)$$

the link is reliable for transmitting real-time data from A to B . For any two reliable links, we assume no difference between the link quality for the real-time service. By the above condition, each MS will determine its active neighbors, which can reliably transmit the real-time data to the MS. The active neighbor table can be established in each MS. Then we can propose the proactive MATPR and the reactive MATPR for real-time service similar as Section 3.2.2 and Section 3.2.3.

4 Simulation Results

The proposed MATPR can minimize the average packet transmission power in CDMA ad hoc networks for both the normal data service and the real-time service. The performance of the MATPR will be verified by the simulations.

4.1 Normal Data Service

The simulated network is composed of 20 – 120 MSs, and each MS is assigned a unique signature sequences. The normalized cross-correlation matrix of the signature sequences is

$$R \triangleq S^T S = \begin{pmatrix} 1 & \rho & \rho & \dots & \rho \\ \rho & 1 & \rho & \vdots & \rho \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho & \vdots & \rho & 1 & \rho \\ \rho & \vdots & \rho & \rho & 1 \end{pmatrix}, \quad (26)$$

The packet length is 255 bytes and the block coding scheme with error correction capability of 15 bits is assumed. All MSs are assumed to have identical transmission power. Suppose the amplitude of the transmitting bits at the transmitter is A , and $10 \log_{10} A^2/\sigma^2 = 15(db)$. The propagation attenuation coefficient is 3.5. Moreover, we normalize the transmission power of one data packet as 1, and the unit distance is defined as the distance at which the signal amplitude will decrease by $1/2$. In Figure 1, we compare the average packet transmission power between the proposed MATPR and the traditional shortest hop distance routing (in the shortest hop distance routing, we assume the transmission radius is 1, the unit distance) for $\rho = 0.1$. Table 1 lists the number of MSs and the MS distribution area.

Table 1. Distribution area.

the number of MSs	distribution area (square area)
20	3 X 3
40	4 X 4
60	5 X 5
80	6 X 6
100	7 X 7
120	8 X 8

It is seen that the average packet transmission power in the MATPR is much less than that of the traditional shortest hop distance routing. Furthermore, with the increase of the number of MSs, the performance gain of the MATPR will increase significantly. In another simulation, the number of

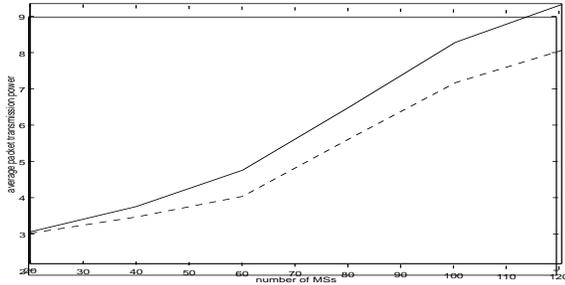


Figure 1. Performance comparison(1).

MSs is fixed to 80, and the distribution area is 3×3 square area. The transmission radius ranges from 0.5 to 1.4. In Figure 2, we compare the relationship between the average packet transmission power and the transmission radius for both the proposed MATPR and the traditional shortest hop distance routing. It is seen that the average packet transmission power in the MATPR is always much less than that of the traditional shortest hop distance routing.

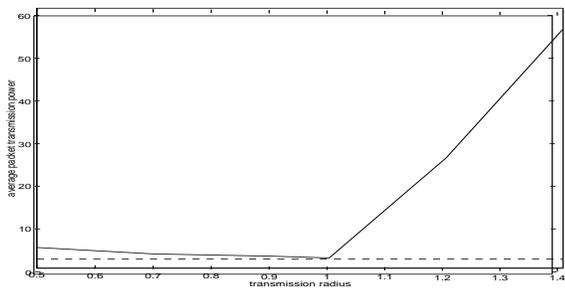


Figure 2. Performance comparison(2).

4.2 Real-time Service

The simulated network is the same as that in Section 4.1. Assume the required BER for the real-time service is 0.01. In Figure 3, the relationship between the average packet transmission power and the number of MSs is illustrated.

5 Conclusion

In this context, we discuss how to minimize the average transmission power utilizing the multiuser detection techniques in CDMA ad hoc networks. For normal data service, jointly considering the multiuser interference, coding scheme and acknowledgment scheme, the link cost is defined, by which the proactive and reactive MATPR is proposed to minimize the average packet transmission power. For real-time service, the condition to determine the reliable

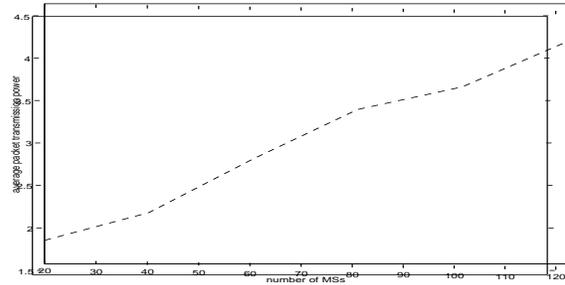


Figure 3. The relationship between the average packet transmission power and the number of MSs.

link is determined, and then we propose the routing method to minimize the average transmission power.

(This research was supported by the Texas Advanced Technology Program under Grant No. 000512-0039-1999.)

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