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Soft handoff in a CDMA wireless ATM environment

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Abstract

Future wireless asynchronous transfer mode (ATM) networks present a number of mobility related challenges. Handoffs due to user mobility require network signaling to maintain the communication link and may result in packet loss due to packet misrouting and/or misordering. This paper proposes a handoff solution for an ATM-based code division multiple access (CDMA) packet switched wireless environment. The proposed solution combines soft handoff and the modified nearest common node rerouting (NCNR) to meet the challenges of wireless ATM. It is shown that, compared with the hard handoff approach, the proposed solution reduces the number of control signals required for handoff and the volume of buffered information packets during handoff, mitigates the problem of packet misrouting and misordering, and significantly improves the radio link transmission accuracy. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Handoff; Wireless multimedia communications; Code-division multiple access; Packet loss

1. Introduction

The wide range acceptance of wireless communications paired with the rapid development in asynchronous transfer mode (ATM) network technology is the basis for the next generation wireless networks [1,2]. It is expected that future wireless networks will provide a broad range of multimedia services (e.g. voice, data, and video) to mobile users with various guaranteed quality of service (QoS). The foreseen "wireless ATM" networks present a number of mobility related challenges [3]. As the number of users increase, cell sizes are reduced to accommodate the increasing service demands, resulting in more frequent handoffs. This illustrates the need for an effective and efficient handoff procedure. In particular, performing "seamless" handoffs is a desirable feature of the wireless ATM. That is, the current QoS must be maintained, as well as packet sequence sustaining to compensate for the possible delay difference between the new and old connections. In general, there are two challenges in the "seamless" handoff:

1. To minimize network signaling required for handoff and rerouting delay due to handoff. ATM networks were originally designed to work with fixed wired terminals, which would retain one virtual channel for each connection throughout the entire call duration. With the support of mobile connections, the wireless ATM networks must be able to handle the access point changing after every handoff. That is, every handoff will require the networks to reroute packets to the new base station (BS). An example is illustrated in Fig. 1. The call was initiated between the mobile terminal (MT) and the fixed wired host, via BS 1. The MT moves out of the service boundary of BS 1 and into the service area of BS 2, which is connected to the wired domain through a different ATM switch. Based on the existing ATM protocols [4], a new virtual connection is required to be set up between BS 2 and the fixed wired host. If the signaling required to reallocate resources is enormous, the handoff routine will be inefficient.
2. To eliminate packet loss due to packet misrouting and/or packet misordering. Although packet loss is tolerated to some degree in voice connections, packet loss is normally not tolerable in data transmission; therefore, frequent packet loss due to handoff is unacceptable. Misrouting may occur in the forward link during handoffs. Misrouted packets are those packets that reach the old BS from the network after the MT has moved to new BS. These packets will be considered lost or may have to be retransmitted by the source. The retransmission can occur only if the connection can tolerate transmission delay. Packet misordering occurs in the reverse link when the MT is sending information packets to the wired network through a virtual connection. Due to handoff, the virtual connection is changed, resulting in the situation that packets from the MT reach the network destination via the new BS virtual connection before the last packet via the old virtual connection. These

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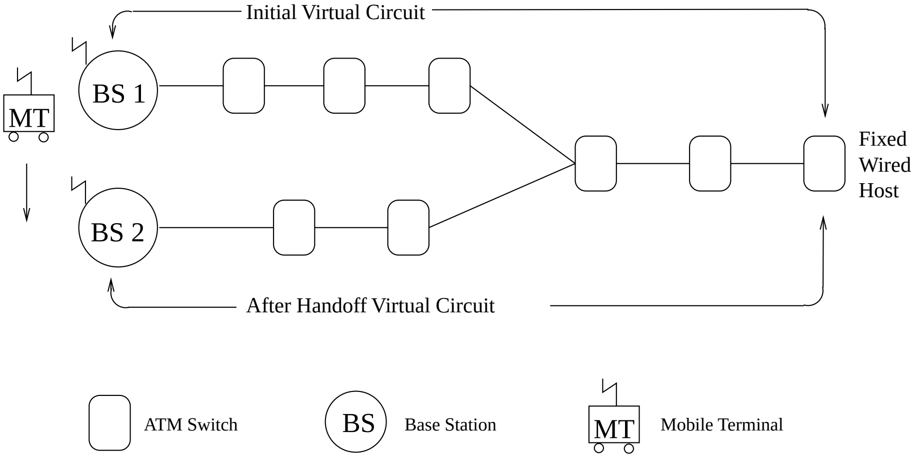

Fig. 1. End-to-end network rerouting.

out-of-order packets will be dropped by the destination since there is no re-assembly in the ATM layer, or may have to be retransmitted by the MT.

To overcome the problems due to handoffs in wireless ATM, this paper proposes a handoff solution which combines soft handoff with a modified “nearest common node rerouting” (NCNR) algorithm. The proposed solution minimizes network resources required for handoff and mitigates the problems of packet loss. We consider an ATM-based direct sequence code division multiple access (CDMA) packet switched network for wireless multimedia communications, and address the handoff issues in the network. With the CDMA, a universal frequency reuse can be implemented which makes it possible for an MT to receive/send the same signal simultaneously from/to two or more different BSs. These simultaneous connections will allow for employing diversity techniques to improve the QoS and to reduce the amount of buffered information. With soft handoff, packet loss due to misrouting and/or misordering can be mitigated. The organization of this paper is as follows. Section 2 describes the proposed handoff solution for the network model under consideration, which uses CDMA in the wireless subsystem. Section 3 investigates the process of network signaling for hard handoff situation and proposes a network control signaling procedure for soft handoff situation. The transmission performance analysis of the proposed soft handoff is evaluated in Section 4, where the noncoherent reverse link and selection diversity are considered. Section 5 gives the conclusions of this work.

2. The proposed handoff solution

The network under consideration uses a hierarchical ATM switching network for interconnection of microcells. MTs share the radio spectrum by using a packetized CDMA protocol. The BSs act as the user network interface between the MTs and the ATM backbone network. Each BS is responsible for packet conversions, wireless connection setup, handoffs, and medium access control in its service area. Several adjacent microcells with relatively low traffic volumes are multiplexed together and connected to an ATM switch node. This reduces the complexity in locating the crossover node between two BSs. The ATM backbone network is responsible for providing the switching and transmission functions, as well as interworking functions with other systems.

The handoff procedure in the network is performed to ensure the continuity of a mobile connection and to minimize interference to the users in the coverage area of neighboring cells. Each handoff includes actions at two levels: radio and network. The radio level handoff is the actual transfer of the radio connection between two BSs; the network level handoff is to support the radio level handoff by performing packet buffering and rerouting. Several network-level handoff algorithms have been previously proposed [5–12], all of which are based on hard handoff at the radio transmission level. Among the algorithms, the NCNR algorithm proposed in [5,6] is a good choice since it has the advantage of minimizing the resources required for rerouting and conserving network bandwidth by eliminating unnecessary connections. On the other hand, due to the fact that the algorithm depends on the “break-before-make” hard handoff process, it has some potential problems which need to be addressed. When the MT is in a region of deep fading, there is a possibility of information loss and poor QoS. That is, the NCNR algorithm does not guarantee packet-loss free communications. Furthermore, with hard handoff, the old BS needs to forward buffered packets to the new BS through the crossover node after the node is identified. The communication link to the new BS can be set up only after the packet forwarding in order to avoid packet misrouting and misordering. Due to the mismatch between high transmission rate over wired links and low transmission rate over wireless links, the number of the buffered packets can be large, which corresponds to a long handoff delay and may result in packet loss. Also, if the number of MTs roaming between radio cells is large, it is possible that the required link bandwidth will exceed the capacity of the BS-to-BS links.

To address the problems due to handoff, the solution proposed here for the radio level handoff is mobile-assisted soft handoff which is realizable with CDMA, because: (a) mobile-assisted handoff requires low signaling load and results in small handoff delay; and (b) soft handoff offers more reliable communication links and allows for higher capacity as compared to hard handoff. Consider soft handoff where an MT is communicating with B (>1) BSs simultaneously during each handoff. In the forward link, coherent detection is possible since each BS transmits a pilot signal for carrier phase synchronization. As a result, the maximum ratio combining at the MT receiver can be implemented for achieving the maximum diversity reception gain. The transmission performance for soft handoff with maximum ratio combining diversity has been evaluated and compared with that for hard handoff [13]. It is concluded that: (a) through proper power control, soft handoff can increase the capacity of a heavily loaded system by more than two times; and (b) soft handoff can double the coverage area of each cell. Over the reverse link, the transmission of a pilot signal for coherent detection is not well justified. As a result, noncoherent detection is necessary. The quasi-optimum noncoherent multipath reception with hard handoff for M-ary orthogonal modulation is illustrated and evaluated for the reverse link in Refs. [13,14]. Different from the forward link, the signal from the MT is received simultaneously by the B BSs at different geographical locations in the reverse link, which makes it very complex to effectively combine the received signals. Hence, the proposed solution uses selection diversity. Each BS makes decision on the transmitted data symbols based on its own received signal and estimates the signal-to-noise ratio (SNR) of the received signal. Among the BSs, only the detected packets from the BS with the highest SNR channel are used. The decision of which BS has the largest SNR is made at the nearest common node, crossover node. There are several possible ways to make this decision and to transfer the information:

1. All the BSs involved in the handoff can send the information packets along with the SNR estimate to the crossover node. Based on each of the B packets received and its associated SNR value, the crossover node determines which packet should be transmitted to the destination;
2. The BSs involved in the handoff procedure can buffer the information packets and send only the SNR estimate to the crossover node. Then the crossover switch can determine from which base station it wishes to receive the information packets. The buffered information will not cause a network overflow because, in the wired domain, the sending of the SNR estimation to the crossover node and the request to one BS for data packet transmission will be very brief and fast. Therefore each BS is not required to have a large buffer size as the BS can discard unrequested information packets fairly often;
3. The crossover node initially picks up a BS with the largest SNR and continues to accept its transmitted packets until there is a significant change in the SNR estimates of the related BS connections.

At the network level, the proposed solution extends the NCNR algorithm to the case of soft handoff. In the forward link, all BSs involved are buffering the same information, due to the simultaneous connections established during the early stages of the handoff process. Therefore the amount of information required to be forwarded from the old BS to the new BS (to ensure correct sequencing of information packets) is smaller than that in the hard handoff case. In the reverse link, packet buffering is not necessary because of the simultaneous connection to all the BSs involved in the handoff. Diversity combining techniques at the crossover node are implemented to preserve data sequence instead of buffering data. Both the forward link and the reverse link of the old connection can be torn down simultaneously. Hence, the proposed solution reduces the probability of packet loss due to handoff and, at the same time, reduces the required buffer sizes at all BSs resulting in less traffic load over the BS-to-BS connections. Furthermore, the proposed solution reduces the number of network control signals required for handoff, as to be discussed in Section 3. The proposed solution, requiring less control signals and smaller amount of buffered information, is easier to implement and is faster to execute. Details of the proposed network level handoff procedure are given in Section 3.2.

3. Network signaling for handoff

This section gives the detail analysis of the network signaling procedure for the proposed soft handoff solution. In order to illustrate the advantages of the proposed solution, the signaling procedure for hard handoff is first studied.

3.1. Signaling for hard handoff

Consider a handoff situation where an MT is moving from the geographical service area of BS 1 and entering the service area of BS 2. The two BSs are connected to the wired network through different access points. There are three possible scenarios which may occur: the general case where there is no direct link between BS 1 and BS 2, and two special cases where BS 1 is a parent of BS 2, or BS 2 is a parent of BS 1. Fig. 2 illustrates the general signaling scheme for hard handoff, where (and in all the subsequent figures):

1. the solid lines represent the established communication links before handoff;
2. the dashed lines represent the new connection links after the handoff;
3. the dotted lines represent the signaling links required during the handoff procedure.

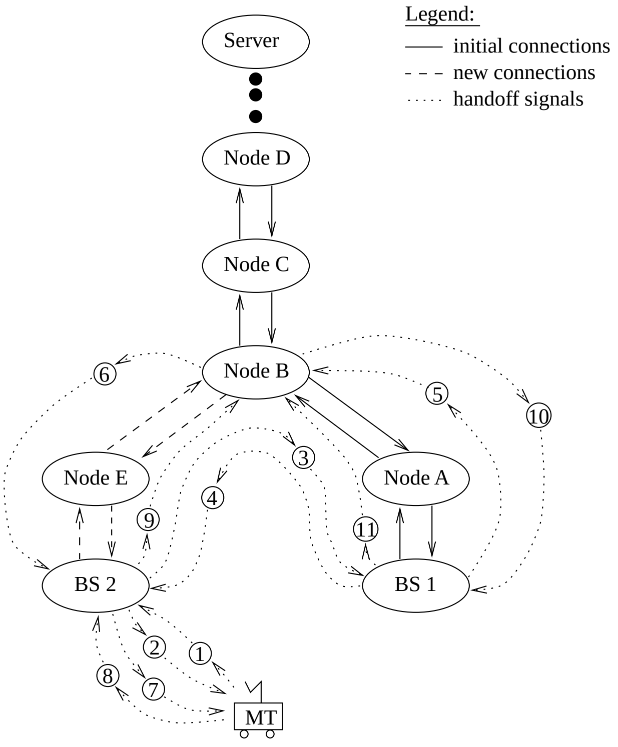

Fig. 2. General signaling procedure with hard handoff.

The server is an ATM node deep within the ATM backbone network. When the MT first arrives in the new radio cell, it sends a greeting signal (signal #1) to the new BS, BS 2, which contains the user identification number, as well as the identity of the old base station, BS 1. Data transmission from the MT to BS 2 begins after BS 2 acknowledges the greeting by sending signal #2. BS 2 then requests that BS 1 forwards the forward link and reverse link data using the BS to BS connections (signals #3 and #4).

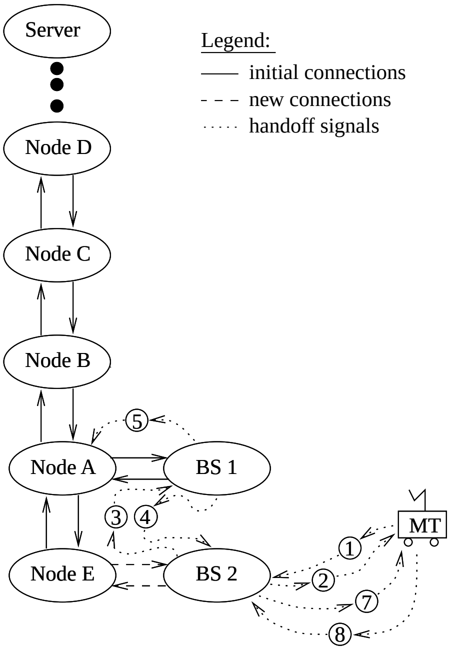

Fig. 3. Signaling procedure with hard handoff when BS 1 is a parent of BS 2.

In order to reuse a portion of the existing connection, signal #3 also implicitly requests on behalf of the new BS that the old BS invokes the distributed crossover point location algorithm. This location algorithm is initiated by the old BS because the new BS has no knowledge of the connection path to the old BS. BS 1 invokes this decision process by backtracking along the original connection route one hop at a time denoted by signal #5. Each node along this route decides whether it knows the appropriate crossover point by examining its routing tables. If the node uses different ports to reach the old and new BSs, it continues to forward this message (nodes A and B in signal #5). The first node that uses the same port to reach both the old and the new BSs (node C) realizes that the node one hop in the forward link direction (node B) is the crossover point. Node C then communicates this fact to node B. Once the crossover point has been identified, the new portion of the connection must be established and the old communication links torn down. The first step, establishing the new partial connection between the crossover point (node B) and the new BS, is performed using signal #6, as it would be in a wired network. This connection is established to the MT using signal #7. If the establishment is successful, acknowledgments are sent from the MT to BS 2 by signal #8 and from BS 2 back along the path to node B by signal #9. Signal #9 is also an implicit request for node B to redirect all data transmitted by the server down the newly established forward link. Buffering at BS 2 is used to allow in-sequence delivery of forward link data packets to the MT. The forward link portion of the connection between node B and BS 1 is then torn down by signal #10. After signal #9, data from the MT can flow directly to the server through BS 2. This reverse link data is buffered at BS 2 to allow the reverse link data forwarded through BS 1 to be first delivered to the crossover point. Once all messages forwarded through BS 1 to the server have been delivered to node B, the reverse link portion of the old connection is torn down by signal #11 and reverse link data flows over the new connection. When all new connections have been created and old connections destroyed, the handoff is complete.

Fig. 3 shows the signaling procedure required when BS 1 is a parent of BS 2, where each of signals #1 to #5 has the same responsibility as that in Fig. 2. Here, node B can easily identify that node A is the crossover point since node B uses the same port (node A) to reach both the old and new BSs. Signals #6 and #9 are not required because signals #3 and #4 have already established the reverse link and forward link communication paths. Signals #7 and #8 are responsible for the radio connection setup and acknowledgment. Upon completion of these two signals, the network knows to free up the communication links between node A and BS 1, hence eliminating signals #10 and #11. Therefore, four signals can be eliminated from those in the general case.

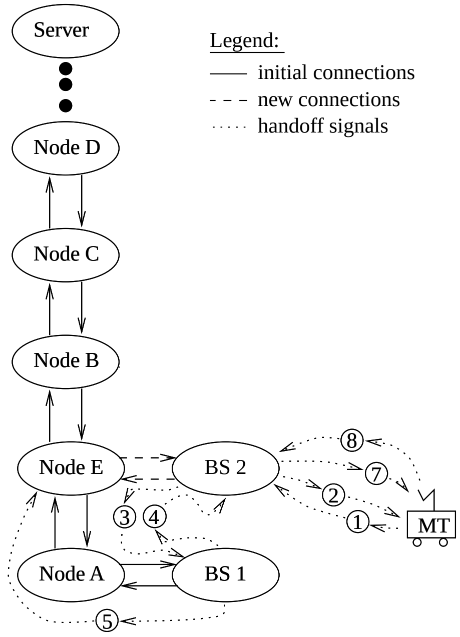

Fig. 4. Signaling procedure with hard handoff when BS 2 is a parent of BS 1.

Fig. 4 illustrates the signal flow when BS 2 is a parent of BS 1. Again, signals #1 to #4 play the same roles as in the general case (Fig. 2). Signal #5 still has the same responsibility but now it stops at node B, because this node is the node that uses the same port to communicate with both the old and the new BSs. Therefore node E is entitled the crossover point here. Again signals #6 and #9 are not required due to signals #3 and #4. Also, with the completion of signals #7 and #8, the network is aware of eliminating the links between node A and BS 1. Therefore, it does not require signals #10 and #11. As a result, four signals can be eliminated as compared with the general case.

3.2. Signaling for soft handoff

With the co-existence of wired and wireless connections in one network, buffering information is a key issue. Wired connections are high speed, while connections between MTs and BSs are slower in speed. Therefore, the transmission rate of information in the forward link direction, from the server to the BSs, will be faster than that from the BSs to the MT. This difference in transmission rate requires the BSs to buffer the forward link data. With reference to the general case in hard handoff, BS 2 is responsible for buffering all information packets destined for the MT until all packets queued up at BS 1 are delivered to BS 2, during the handoff process. All buffered information packets are forwarded from BS 1 to BS 2 to preserve information sequence. Signal #10 is requested once the information forwarding is completed. In the soft handoff situation, BS 2 starts buffering information destined for the MT after signal #6 is completed. At this point all BSs involved in the handoff process are buffering the same information, due to the simultaneous connections established during the early stages of this process. Therefore, the amount of information required by BS 2 from BS 1's buffer, to ensure correct sequencing of information packets, is less than that in the hard handoff case. As a result, in the soft handoff situation the buffer sizes at all BSs can be reduced. The reduced size of buffered information packets results in a reduced load on the BS-to-BS connections of the wired network.

With respect to the reverse link data in hard handoff, the data is buffered at BS 2 to allow the reverse link data forwarded by BS 1 to be delivered to the crossover point first, to ensure proper sequencing of information packets. Once all forwarded information from BS 1 has passed the crossover point, the reverse link portion of the old connection is torn down by signal #11. After the tearing down is completed, reverse link information packets flow directly over the new connection to the destination. With soft handoff, buffering reverse link packets is not necessary because of the simultaneous connections to all BSs involved in the handoff. Diversity combining techniques at the crossover point are implemented to preserve data sequence instead of buffering data. Therefore once the forward link portion of the old connection can be eliminated, so can the reverse link portion. This means that signals #10 and #11 of the general hard handoff case can be reduced to one signal in the soft handoff case, signal #10a. The soft handoff process is illustrated in Fig. 5, where signals common to the hard handoff algorithm have been assigned the same signal numbers as in Fig. 2. The advantage of soft handoff in the signaling procedure is also present in the situation where one BS is a parent of the other. The signal reduction is the same as explained for the general case in soft handoff. That is, signals #10 and #11 are replaced by signal #10a.

In [5,6] it is illustrated that a larger number of signals in the handoff procedure increases the complexity of the signaling software and reduces the speed of the handoff process. Therefore, the smaller the number of signals is, the easier the handoff procedure is to implement, and the faster it will be executed. In this section it has been shown that soft handoff reduces the number of signals and the size of buffered information as compared with those of hard handoff, resulting in simpler and faster handoff process. The proposed handoff procedure also has all other benefits of the NCNR algorithm mentioned in [5].

4. Transmission performance improvement by soft handoff

This section evaluates the transmission bit error rate (BER) performance for the proposed solution over the reverse link, i.e. noncoherent reception with soft handoff using selection diversity. For the simplicity of analysis, consider $B = 2$, having i.i.d. Rayleigh fading α_1 and α_2

with parameter σ^2. The assumption of the common parameter σ^2 is reasonable since in a handoff situation the MT is on the boundary of the two neighboring cells. Considering the M-ary orthogonal modulation for noncoherent detection, with the soft handoff and selection diversity, it can be derived that the probability density function (pdf) of the $M-1$ incorrect correlator outputs, $p_I(z)$, is

$$p_I(z) = \exp(-z), \tag{1}$$

where $z = Z/V$ is the decision variable Z normalized to $V = NI_0$ (N is the number of chips in each symbol interval, I_0 is the power spectral density of noise plus interference). It can also be derived that the conditional pdf, given the channel fading condition $\beta = \max(\beta_1, \beta_2)$ where $\beta_i = \alpha_i^2$ for $i = 1$ and 2, of the correlator output in the presence of the signal is

$$p_C(z|\beta) = \left\{ \frac{\exp[-(z + \beta S^2/V)]}{V} \right\} \varphi_0\left(2\sqrt{\frac{\beta S^2 Z}{V}} \right), \tag{2}$$

where $S^2 = N^2 E_c$ (E_c is the chip energy of the transmitted signal), and $\varphi_0(\cdot)$ is the zeroth-order modified Bessel function. From the theorem on total probability, we have

$$\begin{aligned} p_C(z) &= \int_0^\infty \int_0^\infty p_C(z|\beta) f(\beta_1, \beta_2)\, \mathrm{d}\beta_1\, \mathrm{d}\beta_2 \\ &= \int_0^\infty \int_0^{\beta_1} p_C(Z|\beta_1) f(\beta_1, \beta_2)\, \mathrm{d}\beta_2\, \mathrm{d}\beta_1 \\ &\quad + \int_0^\infty \int_{\beta_1}^\infty p_C(Z|\beta_2) f(\beta_1, \beta_2)\, \mathrm{d}\beta_2\, \mathrm{d}\beta_1 \\ &= \left(\frac{1}{1+\bar{\mu}} \right) \exp\left[-\frac{z}{1+\bar{\mu}} \right] \\ &\quad - \left(\frac{1}{2+\bar{\mu}} \right) \exp\left[-\frac{z}{1+\dfrac{\bar{\mu}}{2}} \right] \\ &\quad + \int_0^\infty \frac{\exp\left(-\dfrac{\beta_1}{\sigma^2} - \dfrac{z}{1+\bar{\mu}} \right)}{\sigma^2(1+\bar{\mu})} \\ &\quad\quad Q_1\left(\sqrt{\frac{2z\bar{\mu}}{(1+\bar{\mu})}}, \sqrt{\frac{2\beta_1(1+\bar{\mu})}{\sigma^2}} \right) \mathrm{d}\beta_1, \end{aligned} \tag{3}$$

where $f(\beta_1, \beta_2)$ is the joint pdf of β_1 and β_2, $\bar{\mu} = \sigma^2 S^2/V$, and $Q_1(\cdot,\cdot)$ is the Marcum's Q function defined as

$$Q_1(a, b) = \int_b^\infty x\, \mathrm{e}^{-\frac{a^2+x^2}{2}} \varphi_0(ax)\, \mathrm{d}x.$$

With the derived $p_I(z)$ and $p_C(z)$, the Chernoff bound of the transmission BER is

$$\begin{aligned} P_e < \min_{\varrho} \Bigg\{ &\int_0^\infty \exp(-\varrho y) \left[\left(\frac{M}{2} - 1 \right) P_C(y) P_I^{\frac{M}{2}-2}(y) p_I(y) \right. \\ &\left. + P_C(y) P_I^{\frac{M}{2}-1}(y) \right] \mathrm{d}y \cdot \int_0^\infty \exp(\varrho x) \\ &\times \left[\frac{M}{2} P_I^{\frac{M}{2}-1}(x) p_I(x) \right] \mathrm{d}x \Bigg\}, \end{aligned} \tag{4}$$

where

$$P_I(x) = \int_0^x p_I(z)\, \mathrm{d}z,$$

$$P_C(y) = \int_0^y p_C(z)\, \mathrm{d}z.$$

For comparison, the bound for soft handoff with equal-gain diversity can be calculated by a direct extension from the analysis of hard handoff. The corresponding pdf's of the correct and incorrect correlator outputs with B independent equal-gain diversity branches are

$$p_I(z) = \frac{z^{B-1}}{(B-1)!} \exp(-z),$$

$$p_C(z) = \frac{z^{B-1}}{(B-1)!} \frac{\exp[-z/(1+\bar{\mu})]}{(1+\bar{\mu})^B}.$$

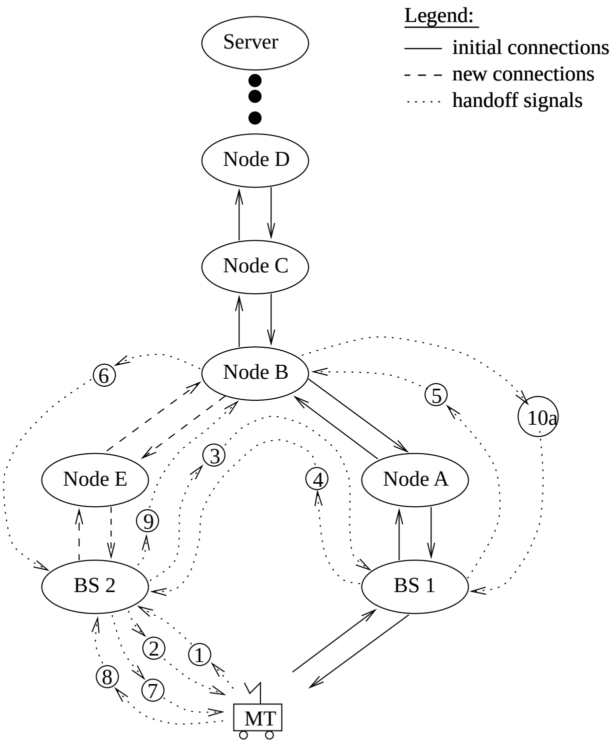

Fig. 5. The proposed signaling procedure with soft handoff.

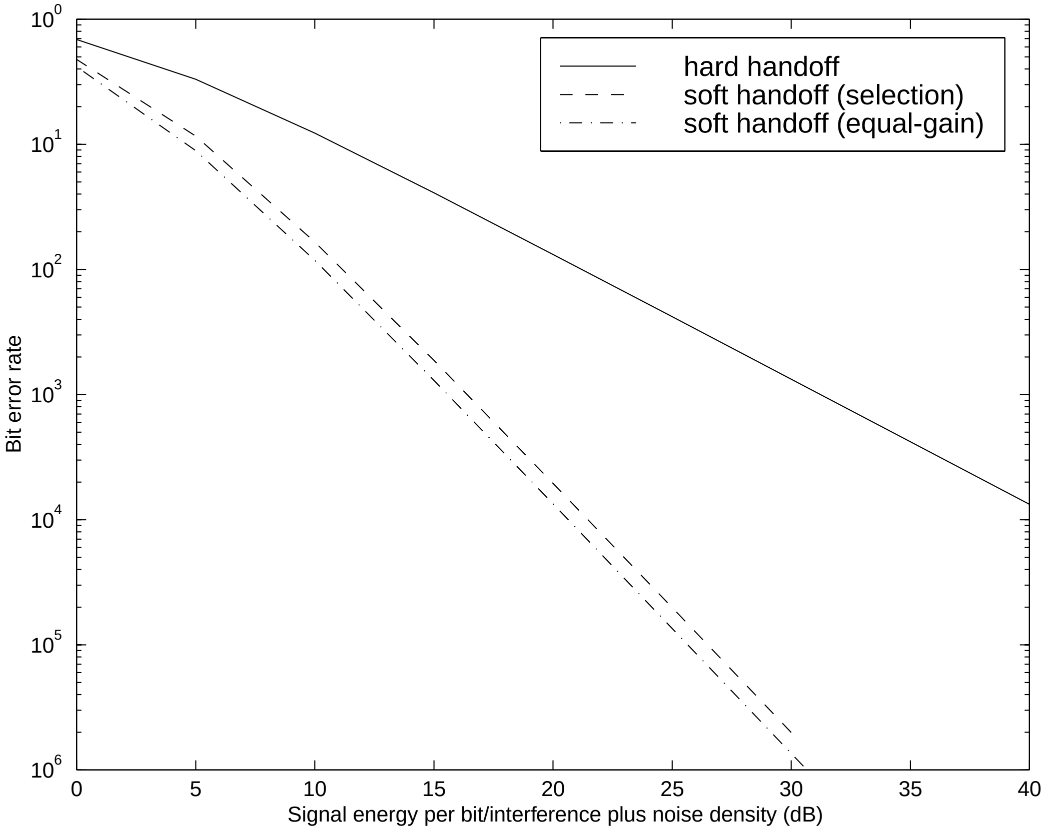

Fig. 6. Chernoff bounds of BER with noncoherent demodulation in hard and soft handoffs.

Eq. (4) can then be used to calculate the BER bound for hard handoff ($B = 1$) and equal-gain diversity soft handoff ($B = 2$).

Fig. 6 shows the numerical results of the Chernoff bound of the transmission BER for soft handoff and for hard handoff. The bound is plotted as a function of the ratio of the average received signal energy per bit to the power spectral density of the interference plus background noise, $\bar{\mu}$, with the Rayleigh fading channel parameter normalized to unit ($\sigma^2 = 1$). The modulation scheme is $M = 64$ orthogonal Hadamard–Walsh encoded binary phase shift keying (BPSK). For a typical voice connection, the required BER is 10^{-3}. The hard handoff approach requires an SNR of 31.2 dB to obtain the 10^{-3} performance level. Soft handoff with equal-gain diversity requires only 15.5 dB, and selection diversity requires 16.4 dB. The figure shows that equal-gain diversity offers an improvement of 15.7 dB while selection diversity offers a 14.8 dB improvement. If the required BER is reduced to 10^{-4}, hard handoff requires 41.4 dB whereas equal-gain requires 20.5 dB, and selection needs 21.4 dB. This again shows the benefit of soft handoff approaches, with equal-gain diversity offering an improvement of 20.9 dB, and selection diversity offering 20 dB improvement.

Between the equal-gain diversity and the selection diversity soft handoffs, equal-gain diversity is not a preferred approach, as the slightly better performance of equal-gain diversity does not justify its complexity and link capacity required. With equal-gain diversity, during the handoff process, each of the BSs involved needs a physical path reserved through the wired network to the crossover node. The traffic can easily exceed the capacity of certain virtual channels and therefore load the wired network with heavy traffic. On the other hand, in selection diversity, only the BS with the highest SNR needs to have a virtual path to the crossover node for information packets. Therefore the selection diversity soft handoff is chosen, due to its improved performance (over hard handoff), its implementation simplicity (as compared with equal-gain diversity), and its requirement for less link capacity from the BSs to the crossover node. The soft handoff can also be seen as a way to prolong the usage of an MT's battery due to the fact that less transmitted signal power is required for the same transmission accuracy as compared with hard handoff.

5. Conclusions

This paper proposes a handoff solution for the wireless/wired ATM packet switched network where CDMA is used for multiple access over the shared radio spectrum. The solution combines soft handoff with the modified nearest common node rerouting scheme to achieve "seamless" handoff and better quality of service. After a detail analysis of the signaling procedure required for hard handoff, the network control signaling procedure with soft handoff is proposed. It is shown that soft handoff not only reduces the required number of the control signals, but also reduces the size of buffered information during handoff. The transmission performance for the noncoherent reverse link using selection diversity and equal-gain diversity respectively in the soft handoff is evaluated. Selection diversity is a better choice because equal-gain diversity requires higher implementation complexity and larger wired link capacity. The proposed solution has the advantages of increasing handoff speed, reducing the network traffic overhead due to handoff, minimizing packet loss probability, and improving the transmission accuracy.

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