Common-Channel Soft Handoff in cdma2000—The Paging Channel

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***Abstract*—cdma2000 has been proposed as the standard in the U.S. for next-generation (3G) mobile phones. This paper describes the proposed paging channel of the cdma2000. It provides both the physical layer details of operation, and the signaling and network issues required to support these new channels. The new paging channel significantly improves the standby times of the phones for the 3G systems. This paper looks at a way to put this common channel in soft handoff, thereby improving the reliability of call setup, and leading to a better standby time for the cdma2000 phones. It is shown that the method does not affect the call setup time, and causes no significant impact on the power budget of the base stations. Furthermore, it is completely backward compatible.**

***Index Terms*—cdma2000, paging channel, soft handoff, standby time.**

I. INTRODUCTION

OF THE various proposals for the third-generation (3G) systems, cdma2000 is currently the leading candidate in the U.S. [1]. It is fully backward compatible with TIA/EIA-95-B [2]. It will support different RF channel bandwidths of the form $N \times 1.2288$ MHz, where $N = 1$ or 3, i.e., 1.2288 Mc/s or 3.6864 Mc/s (called $1x$ and $3x$)—the $3x$ can be multicarrier or direct spread. It supports TIA/EIA-95-B signaling and other signaling, supporting TIA/EIA-95-B services as well as new services. The spreading bandwidths are compatible with TIA/EIA-95-B deployments, and fully supports handoff (HO) to and from existing systems, including IMT-2000 data rates. It will additionally feature advanced medium access control (MAC), different quality of service, and a time-division-duplex (TDD) mode.

The various common forward-link channels include the paging channel (F-PCH: supporting overhead, paging, and base to mobile messaging) and sync channel (F-SYNC: synchronization information and paging channel location). The dedicated channels include dedicated control channel (F-DCCH: MAC control, data, signaling), fundamental channel (F-FCH: voice, data, signaling, control) and supplemental channel (F-SCH: channel for additional services, typically high-speed applications). In this paper, the focus is on the innovations on the paging channel.

A. IS-95 Paging-Channel Procedure

The IS-95 paging channel is used for communications from the base station (BS) to the mobile station (MS) when the MS is not assigned to a dedicated channel. The dedicated channel is called the traffic channel in IS-95 (see [2]). The paging channel carries overhead messages, pages, and acknowledgment to messages sent by the MS on the access channel and channel assignments.

The paging channel is transmitted at a constant rate, either 9600 or 4800 b/s. This is in contrast to the traffic channel, which is variable rate. The paging channel is also transmitted at a constant power, about 10%–15% of the total transmitted power is used for a 9600-b/s channel. This is because the paging channel does not know the required power to reach the MS. Unlike the IS-95 traffic channel, the paging channel is not operated in soft handoff (SHO). The reason for this is that it is difficult to operate this channel in SHO since it is a common channel. To perform SHO on this channel would require that the same information be sent by every BS [3]. The BS that the MS is monitoring is referred to as being in the active set. When the MS is monitoring the paging channel, there is a single active set member. When the MS is on the traffic channel and in SHO, there are multiple members of the active set. Formally, the active set is the set of BS's which are transmitting to the MS (or the MS is monitoring). When the MS is in the system access state, the MS is not allowed to perform HO's. The reason for this is that a specific BS is required for registrations and in order to handle authentication.

B. Paging-Channel Operation

The IS-95 paging channel carries the following type of information: overhead messages (system parameters message, neighbor list message, channel list message, and access parameters message), page messages (general page message), acknowledgment to access channel messages, channel assignment messages (CAM's) (HO direction message, extended HO direction message, and general HO direction message) status requests messages to request information on the MS capabilities, shared secret data (SSD)[1] update, and authentication challenge. Additional information is also carried and described in TIA/EIA/IS-95-A [4]. For all of the messages other than the overhead messages, the messages are addressed to the MS typically by the international mobile station identity (IMSI) or the temporary mobile station identity (TMSI). Other addressing methods, such as the electronic serial number (ESN) can also be used.

C. Basic Paging-Channel Procedures

There are basically the following operating scenarios for the paging and access channel: call origination, call termination, registration, status request, SSD update and unique challenge.

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[1] SSD is used in encryption.

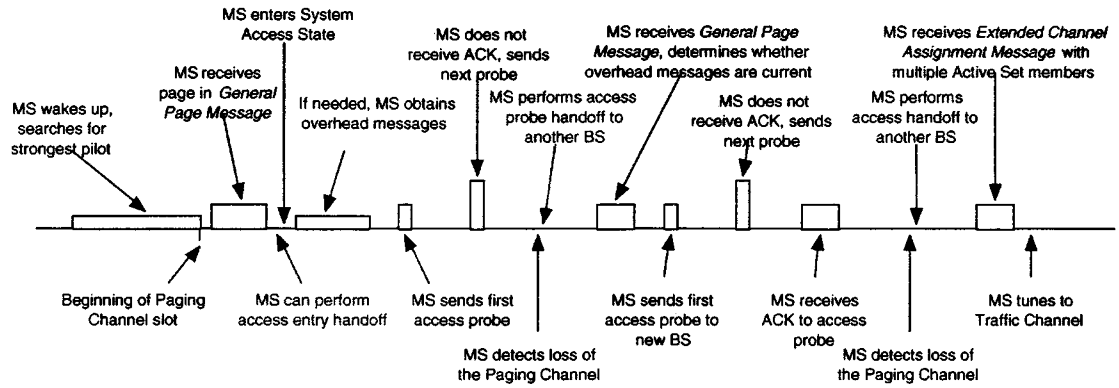

Fig. 1. Illustration of IS-95-B access channel procedures.

For call origination, the MS autonomously enters the system access state and sends the origination message (OM). The BS then sends an acknowledgment. When the channel is set up, the BS sends the CAM to the MS. This provides the information on the dedicated channels that the MS is to use. The MS then begins using the dedicated channels.

For call termination, the BS sends the general page message to the MS. The MS responds with the page response message, which indicates the cell in which the MS is located. When the channel is set up, the BS sends the CAM to the MS. This provides the information on the dedicated channels, which the MS is to use. The MS then begins using the dedicated channels.

When performing an origination or termination, the BS may send a status message, perform an SSD update, or send a unique challenge to the MS. The operations may also be performed without doing a call termination by having the BS send a general page message to the MS to move the MS into the system access state to perform these operations. When the BS has completed these operations, the BS may send a release to the MS or just let the MS time out of the system access state.

For registration, the MS sends the registration message; the BS sends an acknowledgment and then may later send a registration accepted order, a registration rejected order, or a service redirection message.

D. Current IS-95 Performance

Since the paging channel in IS-95 [4] is not operated in SHO, fading and shadowing causes the forward link from one BS to become stronger than the forward link from another BS. This has caused a considerable amount of trouble when performing system accesses, as the MS is not able to perform HO's. Furthermore, calls may be dropped due to the delay in getting the MS into SHO on the traffic channel. In TIA/EIA-95-B, several changes were made to the standard to improve performance. A method, sometimes called "soft channel assignment," was introduced. In this method, the CAM carries a list of BS's, which should be in the MS's active set. By doing soft channel assignment, the MS is placed into SHO when assigned to the traffic channel. This significantly increases the speed in which the MS can be placed into SHO, thus increasing the reliability of the call setup.

Two other methods that were introduced permit HO while the MS is in the system access state. One of these methods is called access probe HO and the other method is called access HO.

Access probe HO permits the MS to switch to monitoring a new BS between access probes. The MS would switch monitoring a new BS whenever the forward link of the BS that the MS is monitoring becomes too weak. Thus, if the MS does not receive the acknowledgment to an access probe and the MS determines that the paging channel is weak, then the MS may shift to using a new BS. Whether the MS is permitted to perform an access probe HO and the set of BS's to which the MS is permitted to perform the access probe HO are contained in the extended system parameters message. For every BS in the MS's neighbor list, the extended system parameters message has a 1-bit flag that indicates whether an access probe HO is permitted to that BS.

Access HO permits the MS to switch to monitoring a new BS while waiting for the CAM. Thus, if the MS has received an acknowledgment to its access probe and the MS determines that the paging channel is weak, then the MS may shift to using a new BS. Whether the MS is permitted to perform an access HO and the set of BS's to which the MS is permitted to perform the access HO are contained in the extended system parameters message. For every BS in the MS's neighbor list, the extended system parameters message has a 1-bit flag that indicates whether an access HO is permitted to that BS.

A final method, which is not important for this discussion, is access entry HO. This permits the MS to begin monitoring a new BS from the time in which the MS receives a page until it transmits the page response message. Fig. 1 illustrates the IS-95-B access procedures.

In the transmitted pilot measurement information (PMI), each pilot above a predetermined threshold (T_{ADD}) is listed. For each pilot, its phase, strength, and other information (e.g., whether it can do HO) are included. The pseudonoise (PN) phase is the phase of the pilot being reported. This identifies the BS and also provides information on the timing of the BS's forward link relative to the reference BS. A flag named ACCESS_HO_EN indicates whether this pilot is in the ACCESS_HO_LIST. This list is the list of BS's with which the MS would be likely to perform an access HO or an access probe HO. This list is established when the MS first begins sending probes on the access channel. The active pilot strength is the E_c/I_0 of the pilot in the active set. The MS sets a flag to "1" if the active BS is the one in which the MS transmitted the first access probe. If the BS is in the active set is not the BS to which the MS transmitted the first access probe, then this flag is set to "0" and the first pilot in the list is the one in which the MS transmitted the first access probe.

II. Structure of the cdma2000 Paging Channel

cdma2000 is currently the leading candidate for the third-generation (3G) standard in the U.S. [1]. The organization of cdma2000 common channels will be a structure consisting of three forward link physical channels: the F-QPCH (quick paging channel), the F-BCCH (broadcast channel), and the F-CCCH (common control channel). The F-QPCH carries indications of pages directed to the MS. The BS transmits on the F-QPCH whenever the BS needs to contact a MS operating in slotted mode. The F-BCCH carries overhead information and broadcast short messages. Overhead information is not required to be continually transmitted; broadcast messages are only required to be transmitted when a broadcast message is to be sent. The F-CCCH is transmitted when the BS responds to the MS. All messages on the F-CCCH can be transmitted to the MS in a SHO mode. Furthermore, all messages can be transmitted to the MS with approximately the amount of power needed to contact the MS. These techniques result in greater overall system capacity and greater reliability [5]. Further details can be found in [6].

A. Details of Operation—Controlling Soft HO

In the overhead messages, the BS lists the BS's that are permitted to transmit to the MS in SHO on the F-CCCH and F-QPCH. It should be noted that the IS-95-B access HO and access probe HO may be performed with some BS's and SHO performed with other BS's. In particular, IS-95 has a flag for every member of the neighbor list for which access HO and access probe HO are permitted. A flag is introduced for every member of the neighbor list in which SHO is permitted on the F-CCCH. A separate flag is introduced for every member of the F-QPCH. This is illustrated for five cells with three sectors each, shown in Table I.

In Table I, ACS refers to the access HO flag, CCS to the F-CCCH SHO allowed flag, QCS to the F-QPCH SHO allowed flag, and AcHO implies that access HO is allowed. The MS is located in sector A1. New MS's are permitted to perform SHO on the F-CCCH with all sectors in cells A and B. The MS is not permitted to perform SHO on the F-CCCH with sectors from other cells. It should be noted that it may be desirable to restrict SHO on the F-CCCH to only sectors of the same BS. In this case, SHO of the F-CCCH would be only to A2 and A3. This is because it is easier to synchronize and control the SHO from a cell where only single processor is involved. It also permits layer 2 to be fully run from the base transceiver station (BTS). The example also shows that SHO on the F-QPCH may be done in cells A, B, and C. A wider number of cells may be used for SHO on the F-QPCH since paging can be more readily handled from a central controller. However, this is not required and there is total flexibility in set of cells that permit SHO on the F-CCCH.

TABLE I
Illustration of the SHO Flags

BS	ACS	CCS	QCS	Comments
A2	1	1	1	AcHO, F-CCCH/F-QPCH SHO
A3	1	1	1	AcHO, F-CCCH/F-QPCH SHO
B1	1	1	1	AcHO, F-CCCH/F-QPCH SHO
B2	1	1	1	AcHO, F-CCCH/F-QPCH SHO
B3	1	1	1	AcHO, F-CCCH/F-QPCH SHO
C1	1	0	1	AcHO, F-QPCH SHO
C2	1	0	1	AcHO, F-QPCH SHO
C3	1	0	1	AcHO, F-QPCH SHO
D1	1	0	0	AcHO
D2	1	0	0	AcHO
D3	1	0	0	AcHO
E1	0	0	0	No HO
E2	0	0	0	No HO
E3	0	0	0	No HO

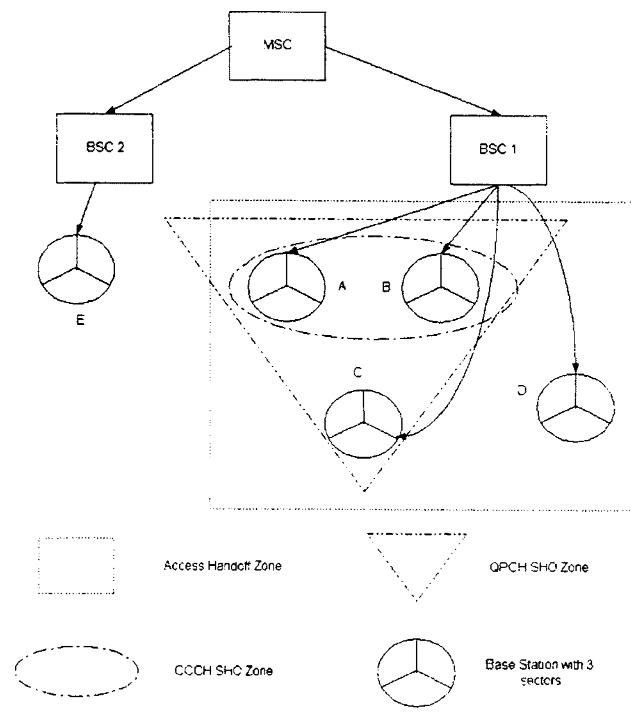

Fig. 2. SHO on F-QPCH.

Note that SHO on the F-QPCH is not permitted for cell D. This may occur since cell D is in a different registration zone. No forms of HO are permitted to cell E. This may be because it is controlled by a different base-station controller (BSC). Fig. 2 illustrates the scenario.

This will be used as a prototype for the remainder of this paper. Now, the three components of the paging channel—F-QPCH, F-CCCH, and F-BCCH are described.

III. Structure of the F-QPCH

The quick paging channel contains single bit messages to direct slotted-mode MS's to monitor their assigned slot on the paging channel. The F-QPCH data rate is 9600, 4800, or 2400 b/s, and is specified in an overhead message. Each single bit message is transmitted twice per 80-ms slot. The F-QPCH bit detection is pilot aided coherent on–off keying (OOK).

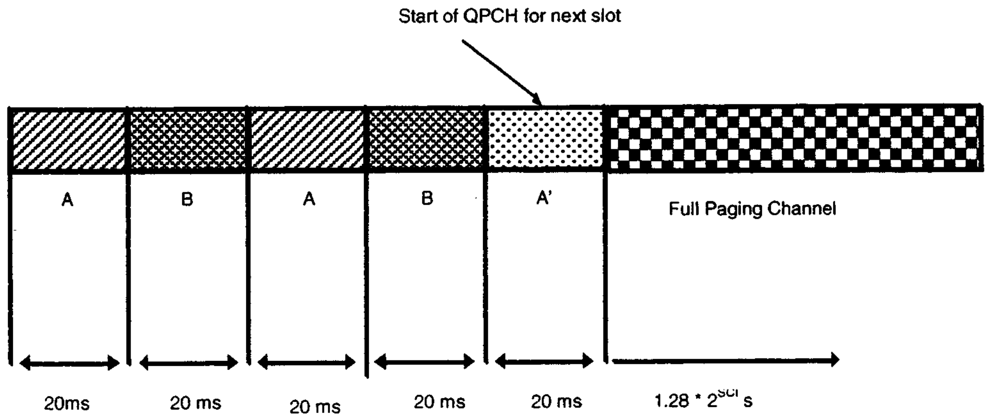

Fig. 3. F-QPCH time line.

Using Little's formula $(N = \lambda T)$, if we assume 30 Erlangs of traffic per sector, and an average call duration (T) of 120 s, we get $\lambda = 1/4$ call setups per second per s sector. Assuming 30% of them to be mobile terminated and two pages per call setup, we have 0.15 calls per second, or one call every 6–7 s on an average. Thus, the probability of an MS being falsely paged due to network load is relatively small [7].

A. F-QPCH Signaling

Let t denote the start time of the paging channel or the forward common control channel. Group-A MS receives the first paging indication symbol between $(t - 100)$ ms and $(t - 80)$ ms, and second symbol between $(t - 60)$ ms and $(t - 40)$ ms. Group-B MS receives the first paging indication symbol between $(t - 80)$ ms and $(t - 60)$ ms, and second symbol between $(t - 40)$ ms and $(t - 20)$ ms. The time line of the quick paging channel is shown in Fig. 3. The term SCI refers to slot cycle index ($\mathrm{SCI} \in \mathbb{N}$, usually 0, 1, or 2). The length of the paging channel slot cycle is $1.28 \times 2^{\mathrm{SCI}}$ s.

If the first paging indication bit is set to zero, the MS can go back to sleep. If the first paging indication bit is set to one, the MS receives the second paging indication bit. If the second paging indication bit is set to zero, the MS can go back to sleep. If the second paging indication bit is set to one, the MS receives the paging channel in the following paging channel slot.

To determine the MS's assigned bit positions, the MS needs to use a hash function, to provide a uniform distribution of MS's among N slots. Using as arguments the MS's IMSI or ESN, the number of slots N, and a modifier DECORR (to decorrelate the values obtained for the various applications from the same MS), as hashing function is constructed. The HASH_KEY is a 32-bit number derived from the IMSI. Word L is bits 0–15 of HASH_KEY, and word H to be bits 16–31 of HASH_KEY where bit zero is the least significant bit of HASH_KEY. For determining MS's assigned paging indication bit positions in the 80-ms time slot before the assigned paging channel slot, in units of paging indication bits (128 or 256 PN chips for 9600- and 4800-b/s data rate, respectively), the hash value is computed as follows: $R_1 = \lfloor N_1 \times ((40503 \times (L \oplus H \oplus \mathrm{DECORR}_1)) \bmod 2^{16})/2^{16} \rfloor$ and $R_2 = \lfloor N_2 \times ((40503 \times (L \oplus H \oplus \mathrm{DECORR}_2)) \bmod 2^{16})/2^{16} \rfloor + N_1$. Here, $N_1 = 384(192)$ and $N_2 = 192(96)$ for 9600 (4800) b/s, and $\mathrm{DECORR}_1 = \lfloor t/64 \rfloor \bmod 2^{16}$ and $\mathrm{DECORR}_2 = \lfloor t/64 + 1 \rfloor \bmod 2^{16}$, where t refers to the system time. The F-QPCH rate is transmitted on F-BCCH.

B. Performance of the F-QPCH

The F-QPCH bit is decoded coherently. The pilot is used to provide the phase reference for doing so. Multiple paths may be combined using the maximal ratio combining, as described in [8]. To obtain a reliable estimate, the decision is tri-valued (erasure, one, or one). If the pilot level falls below a certain threshold, the bit is declared an erasure, else the bit is detected in the regular way. This threshold is tuned to keep the miss probability within acceptable limits.

The F-QPCH bit detection is pilot aided. Hence, coherent OOK and coherent binary phase shift keying (BPSK) are considered as possible modulation schemes. OOK conserves average energy when the probability of transmitting a "1," $p < 0.25$ [7]. As an example, for eight pages per 80 ms (rather high) at 9600 b/s, $p = 8/384 = 0.021$. Thus, OOK saves about 5% power over BPSK, and is chosen as the preferred method. For a fading channel, the situation has been analyzed [7].

To facilitate the discussion, first consider a few definitions. Let $\hat{I}_{\mathrm{or}}$ denote the total received signal power density, N_0 the thermal noise power density, and I_{oc} the interference power density due to other cells. The geometry G of a MS is defined to be $G = \hat{I}_{\mathrm{or}}/(N_0 + I_{\mathrm{oc}})$. The utility of this parameter stems from the fact that a higher geometry implies that the MS is well within the cell of a BS. If we assume that N_0 is dominated by I_{oc}, a 0-dB geometry implies that the MS is at a cell boundary (in reality, a slightly negative geometry due to N_0). A very negative geometry usually means that the MS is not listening to the optimal BS or is going out of coverage. Let E_b denote the received energy per bit, E_c denote the transmitted per chip energy, I_{or} denote the transmitted signal strength, W denote the chip rate,

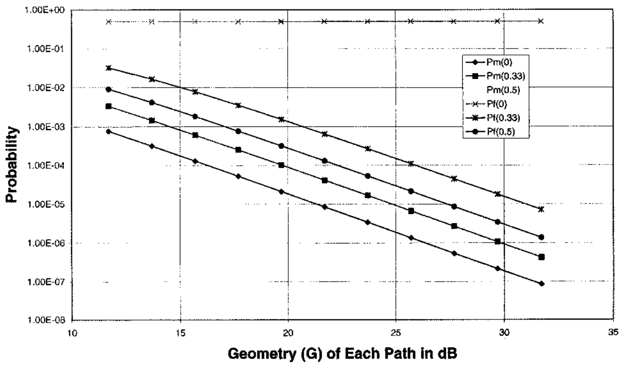

Fig. 4. Performance of F-QPCH in SHO at cell boundary.

R denote the bit rate, P denote the path loss, and N_t denote the total noise and interference power density at the receiver. Since $P \times I_{\rm or} = \hat{I}_{\rm or}$, the SNR Γ is given by

$$\Gamma = \frac{E_b}{N_t} = \frac{\dfrac{E_c}{I_{\rm or}} \times P \times \dfrac{W}{R}}{\dfrac{N_0 + I_{\rm oc}}{I_{\rm or}}} = \frac{E_c}{I_{\rm or}} \times \frac{W}{R} \times \frac{\hat{I}_{\rm or}}{N_0 + I_{oc}}.$$

This gives an expression for the transmitted power in terms of the geometry G, the spreading gain Ψ, and the received SNR Γ. Measuring in decibels

$$\frac{E_c}{I_{\rm or}} = \Gamma - \Psi - G.$$

If P equally strong BS's with energy $\beta^2 \mathcal{E}$ per path are received, the average SNR per channel is $\overline{\gamma_c} = (\mathcal{E}/N_0)E[\beta^2]$. The total SNR then has pdf $p(\gamma) = (1/(P-1)!\overline{\gamma_c}^P)\gamma^{P-1} e^{-(\gamma/\overline{\gamma_c})}$, $\gamma \geq 0$. Let $\mu = \sqrt{((1-\xi)^2\overline{\gamma_c})/(1+(1-\xi)^2\overline{\gamma_c})}$ and $\ell = \sqrt{\xi^2\overline{\gamma_c}/(1+\xi^2\overline{\gamma_c})}$ Defining P_m as the probability of missing a page, and P_f of falsely deciding that there was a page when there is no page, i.e., a false alarm, the error probabilities are given by [9]

$$P_m(\mu) = \left(\frac{1-\mu}{2}\right)^P \sum_{k=0}^{P-1} {}^{P-1+k}C_k \left(\frac{1+\mu}{2}\right)^k$$
$$P_f(\ell) = \left(\frac{1-\ell}{2}\right)^P \sum_{k=0}^{P-1} {}^{P-1+k}C_k \left(\frac{1+\ell}{2}\right)^k.$$

Thus, it is sufficient to plot the performance of the F-QPCH only in terms of the geometry of the MS. For a transmitted $E_c/I_{\rm or} = -10$ dB, for two paths, the performance of the F-QPCH is plotted in Fig. 4. For a detailed discussion on the gains of using SHO, the reader is referred to [9].

IV. Call Termination and F-QPCH Operation

To show the operation of the F-QPCH, we use a call termination, as shown in Fig. 5. It uses the BS's and various flags that have been previously described. As was previously discussed in Section II-A, SHO may be restricted to a single BTS. In what follows, it is assumed that SHO is permitted on the F-QPCH between BTS's.

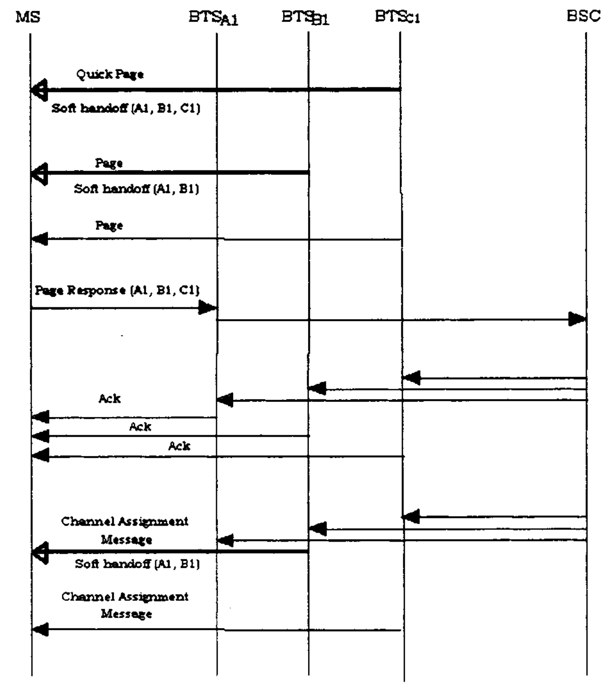

Fig. 5. Illustration of call termination.

The BS sends a quick page at a particular time that is given by the IMSI of the MS and the configuration of the BS. Typically, the configuration of all BS's in a paging region are configured the same so all BS's would be transmitting the quick page at the same time. For those BS's that transmit the quick page at the same time, the MS can combine these BS's in SHO. For a particular BS, the overhead messages would have the QCS flag set to one for a neighboring BS when the neighboring BS sends the same quick pages, and at the same time. In the above example, BS A1 would set QCS to 1 for BS's A2, A3, B1, B2, B3, C1, C2, and C3. BS D1, D2, and D3 do not have QCS set to one. This is since these BS's are not in the same paging area or are otherwise unable to transmit the quick page at the same time. When monitoring the appropriate slot on the F-QPCH, the MS combines the transmissions from multiple BS's in a SHO mode. The MS then determines whether it has received a quick page. It should be noted that the MS is not required to combine signals from other cells in the same slot that are not in SHO. This is because the MS would pick up the strongest BS when receiving the quick page. However, there would be some benefit if the MS knew the configuration of the neighboring BS and, thus, could also process the quick page transmitted by a neighboring BS. However, the MS may not have received the configuration information from the neighboring cell and, thus, may not know the time that the quick page is being transmitted. It should be noted that the neighboring BS would typically use the SHO mode with a neighboring BS if the neighboring BS were sending the power control bits in the same slot [10].

After the MS has been alerted by the quick page, the MS begins to monitor the F-CCCH. The BS will then send a page message, similar to a normal page, on the F-CCCH. This message contains the full address of the MS. It should be noted that full

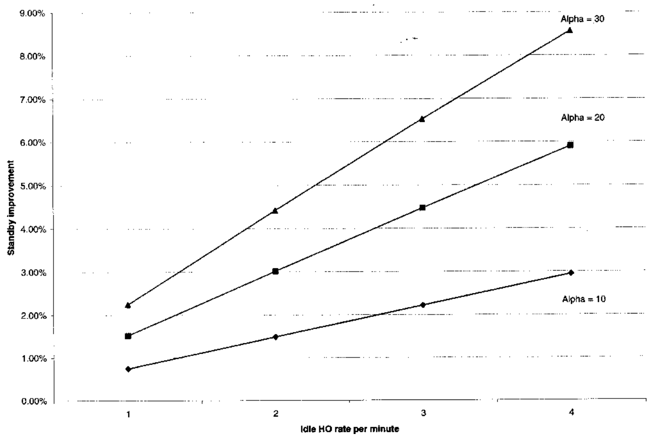

Fig. 6. Standby-time improvement.

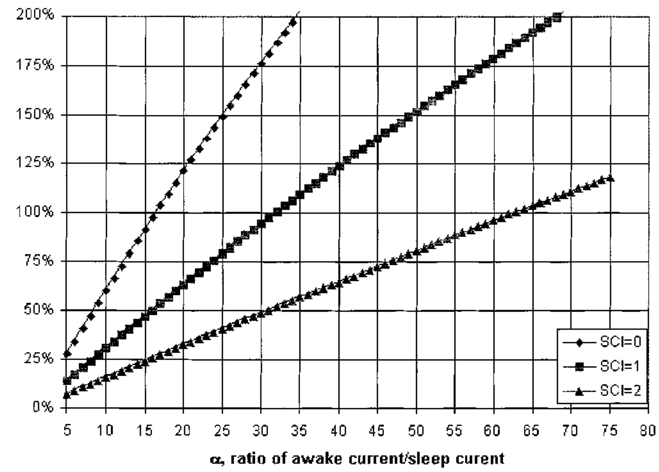

Fig. 7. F-QPCH: 3-bit combining (SHO with signal strengths $E, E/2$ and $E/2$).

page step is not required and the MS could respond directly with the page response message after receiving the quick page. However, the false alarm rate on the quick paging channel may be sufficiently high so that it is preferable for the MS to wait for the page message before sending the page response message.

V. Controlling Handoff

As outlined in Section X, the phone standby time can be increased if it had knowledge of the change in the F-BCCH. To this end, two indicator bits are multiplexed onto the F-QPCH to indicate if the F-BCCH has changed in the last 10 min. These bits must not be used in SHO, as they are BS specific. The MS monitors these bits, and revisits the F-BCCH if only they are set. This is particularly useful when the idle HO rate is very high, as in a subway. The MS can store all the parameters of each BS, and not need to reread the F-BCCH if it switches back and forth between multiple BS's.

The number of page bits per F-QPCH slot are two, and the number of configuration bits (NC) are also two, spaced every 40 ms. Let $\delta = 60\%$ of the possible idle HO pilots be known to the mobile. Let $S = 90$ ms be the wake up time per assigned slot, and $W = 4$ ms be the wake up time per F-QPCH bit, $f_o = 0.31\%$ is the percentage of wake up time due to only F-QPCH bits. Let N be the number of idle HO's per minute. Then, without configuration bits, the fraction of the time mobile wakes (f_{WO}) up for is given by $f_{\mathrm{WO}} = f_o + (N \times S)/60000$. With the bits, this fraction is: $f_W = f_o + (N \times (S \times (1-\delta) + [\mathrm{NC} \times W \times \delta]))/60000$. Define α to be the ratio of awake current to sleep current, the standby-time improvement β is given by

$$\beta = \frac{1 + f_{\mathrm{WO}} \times (\alpha - 1)}{1 + f_W \times (\alpha - 1)} - 1.$$

For various values of α, Fig. 6 is obtained. The improvements are great for higher values of α and, thus, is a desirable feature for future phones where the sleep current is expected to go down a lot.

A. Power Requirements

Note that the F-QPCH bits could be sent in SHO, but the configuration bits cannot be sent in SHO. This requires different power levels for same level of reliability. In fact, these bits should not be missed with probability more than 10^{-4}. The cost of false alarm is not as much. However, note that since we do threshold decoding at the decoder, it is possible to threshold this bit differently to get a different set of false alarms.

Using the notation used in Section III-B, for a 9.6-kb/s channel, $\Psi = 10\log_{10}128 = 21.1$ dB, and for 4.8 kb/s, $\Psi = 10\log_{10}256 = 24.1$ dB. From the performance curves, an error probability of 10^{-4} is very hard to achieve for 1-bit combining. Realistically, a target of 10^{-3} is achievable. It is suggested that we use a lower threshold to compensate for too high peak-to-average ratios and trade misses for false alarms.

The general performance has been well analyzed [9]. Here, another case of interest is presented that will aid in the design of the network. The data rate is assumed to be 9600 b/s.

Fig. 7 plots the BS's in SHO in signal strengths $E, E/2$ and $E/2$. From the curves, it is clear that we need to combine multiple bits. Three-bit combining allows operating at a reasonably low E_c/I_{or}. For $G = -1$ dB, $E_c/I_{\mathrm{or}} = -10$ dB. For additive white Gaussian noise (AWGN), the same performance is obtained for simply 1 b.

B. Spacing of the Bits

The autocorrelation function of the fading process can be approximated by $J_0(2\pi f_d t)$ [11], where $J_0(x)$ is the Bessel function of zeroth order. Thus, if the Doppler frequency f_d is ν Hz, for two samples to be independent, we seek the first zero of this function, which is roughly at 2.4. This evaluates to $t = 0.382/f_d$ s. There is no major effect on the diversity gain when the correlation $\rho \leq 0.5$ [12], and $t \leq 0.191/f_d$ s. This will be 30 ms for a 6-Hz fading, and 3 ms for 60-Hz fading.

Table II lists the recommended values for 9600 b/s. Reduce the E_c/I_{or} by 3 dB for 4800 b/s. Hence, the recommended operating point of the channel is at $E_c/I_{\mathrm{or}} = -10$ dB with the bits spaced 40 ms apart.

VI. Effects of Phase Error on F-QPCH—$3x$ Systems

For $3x$ systems, the F-QPCH is used with different users along the in-phase (I) and quadrature (Q) axes [13]. This leads to potential problems with power leakage between the

TABLE II
INDICATOR BIT OPERATING POINT

Channel Type	Geometry(in dB)	PMiss	PFalse	No. of Bits	Required Ec/Ior (dB)
AWGN	0	10^{-4}	10^{-4}	1	-10
6Hz Fade	-6	0.005	0.01	1	-6
6 Hz Fade	-3	10^{-4}	0.001	2	-7
6 Hz Fade	0	10^{-4}	10^{-3}	3	-11
60 Hz Fade	0	0.001	0.01	1	-9
60 Hz Fade	0	10^{-4}	10^{-3}	2	-10

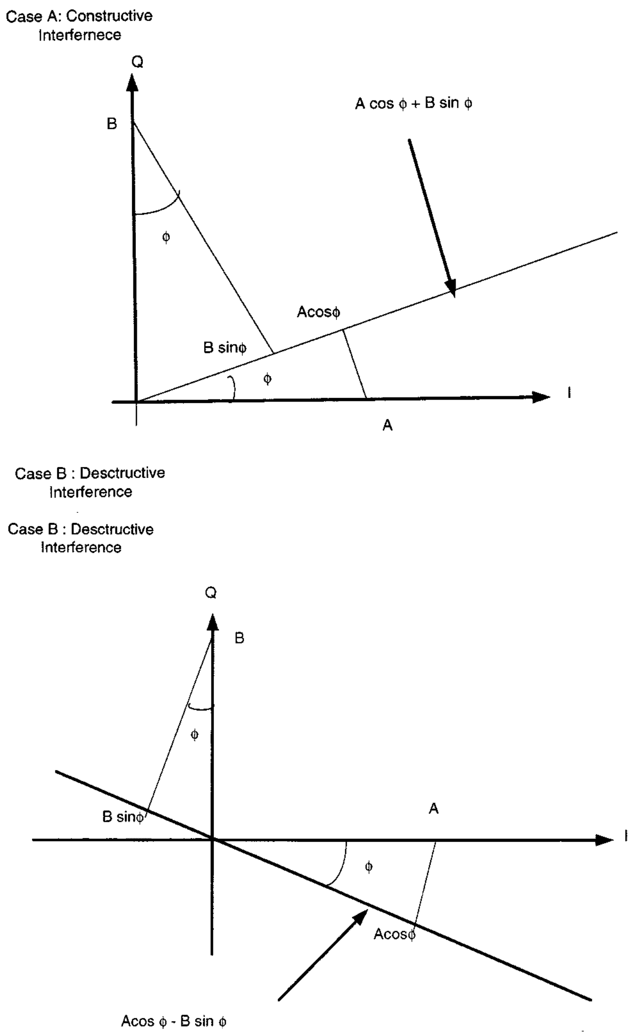

Fig. 8. Effect of phase error on F-QPCH.

two channels. This is analyzed here. Two cases of interest are shown, which cover all the possibilities, as in pilot-aided detection, phase errors will be certainly less than $\pi/4$. To analyze the situation, consider Fig. 8.

The effect is then quantified for amplitudes A and B along in-phase and quadrature axes. For constructive interference, the resultant signal is $A\cos\phi + B\sin\phi$. For destructive interference, the resultant signal is $A\cos\phi - B\sin\phi$. For various values of A and B, Table III is obtained, where the loss or gain is normalized by signal power, G denotes gain, L denotes loss, and F leakage power.

TABLE III
EFFECT OF PHASE ERROR ON F-QPCH

Case	A	B	Constructive	Destructive
1	1	0	L: $\cos^2\phi$	L: $\cos^2\phi$
2	0	1	F: $\sin^2\phi$	F: $\sin^2\phi$
3	1	1	G: $1+\sin 2\phi$	L: $1-\sin 2\phi$

TABLE IV
PERFORMANCE OF F-QPCH WITH PHASE ERRORS

Phase Error	1C/D	2C/D (*)	3C	3D
0^o	0	$-\infty$	0	0
1^o	-0.001	-35	0.15	-0.15
5^o	-0.033	-21.2	0.7	-0.83
10^o	-0.13	-15.2	1.28	-1.82
25^o	-0.86	-7.47	2.47	-6.32

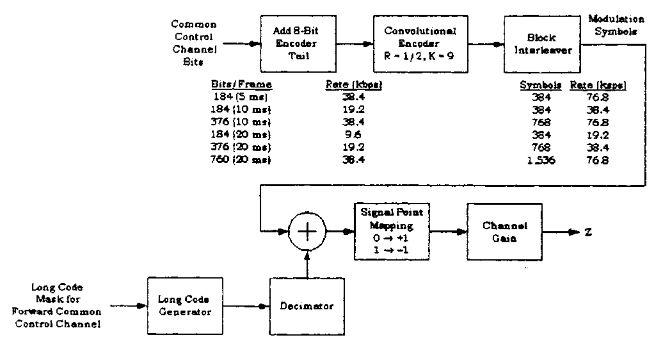

Fig. 9. F-CCCH modulation.

These cases, as numbered in the first column of Table III, are outlined in Table IV for various possible phase errors. A positive entry implies gain, a negative entry implies loss, and an asterisk denotes spurious signals that may raise the false alarm rates. C denotes constructive interference, and D denotes destructive interference.

For OOK signals, up to 5° phase error estimate, the performance is not hurt by more than 1 dB; however, at 10°, it may be worse by 2 dB. The leakage spillover power is pretty low, less than 7 dB at 25°, thus, the effect may not be too bad. The use of a suitable diversity technique like orthogonal time diversity has been proposed to mitigate this effect.

VII. PHYSICAL LAYER OF THE F-CCCH

The F-CCCH is generated according to Fig. 9. The rate and number of frames sent is selected on a per message basis. It is

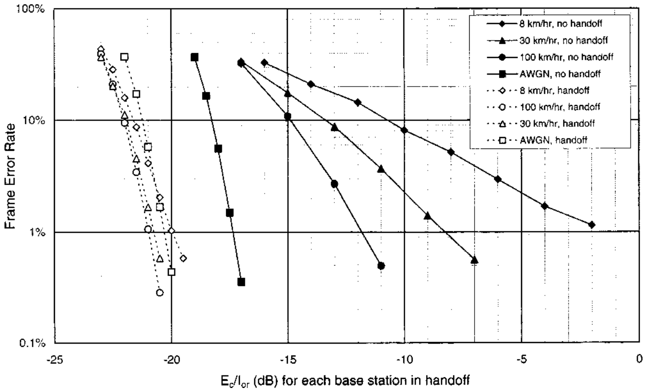

Fig. 10. 13-dB plot. One path per BS. Forward-link simulation results (rate set 1: 9600 b/s). HO versus no HO, one path per BS, per path $\hat{I}_{\rm or}/N_0 = 10$ dB.

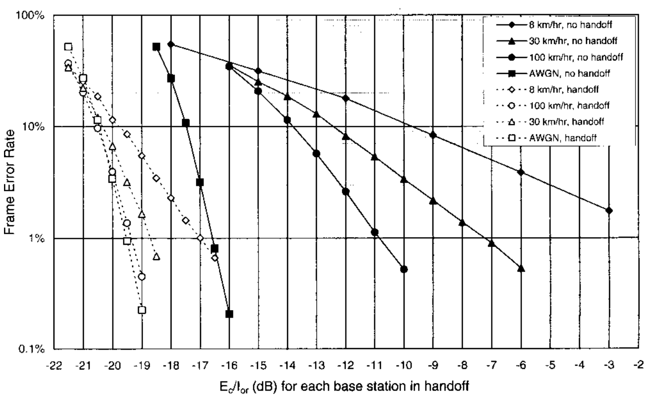

Fig. 11. 8-dB plot. One path per BS. Forward-link simulation results (rate set 1: 9600 b/s). HO versus no HO, one path per BS, per path $\hat{I}_{\rm or}/N_0 = 5$ dB.

turned off when there are no messages to send in order to save power and increase capacity. The F-CCCH carries general page messages, CAM's, status request messages, etc.

To study the gain of SHO over hard handoff (HHO) on F-CCCH, let N_0 be the noise (including interference) power at the receiver, and $I_{\rm or}$ the transmitted signal strength. Define $\xi = I_{\rm or}/N_0$. The legend can be interpreted as follows: SHO refers to soft handoff, HHO refers to hard handoff. The numbers in decibels refer to the received ξ. Thus, for a 6-dB plot with two BS's with two paths per BS, per path $\xi = 0$ dB. If there were only one path per BS, per path ξ would be 3 dB. These are obtained at carrier frequency of 1960 MHz and 1.25-MHz bandwidth.

The following examples are provided for data rate of 9.6 kb/s for two equal strength BS's with one path each.

- $\xi = 10$ dB. This gives the 13-dB plot. (Fig. 10).
- $\xi = 5$ dB, i.e., received $\rm SNR = 8$ dB in SHO. (Fig. 11).

The following examples are provided for data rate of 9.6 kb/s for two equal strength BS's with two paths each.

- $\xi = 7$ dB. This gives the 13-dB plot. (Fig. 12).
- $\xi = 2$ dB, i.e., received $\rm SNR = 8$ dB in SHO. (Fig. 13).

The performance indicates a strong benefit of doing SHO on F-CCCH. Note that there is a 3-dB gain from using the power

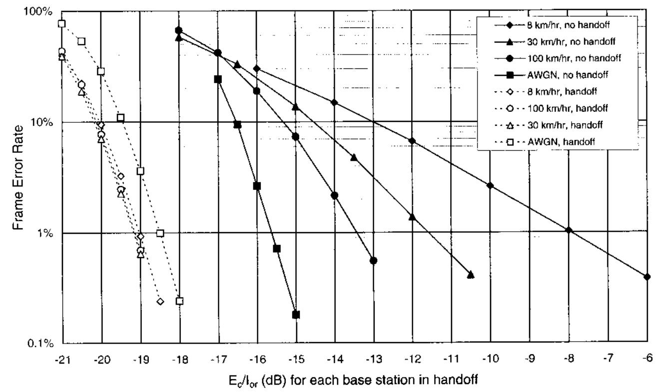

Fig. 12. 13-dB plot. Two paths per BS. Forward-link simulation results (rate set 1: 9600 b/s). HO versus no HO, two paths per BS, per path $\hat{I}_{\rm or}/N_0 = 2$ dB.

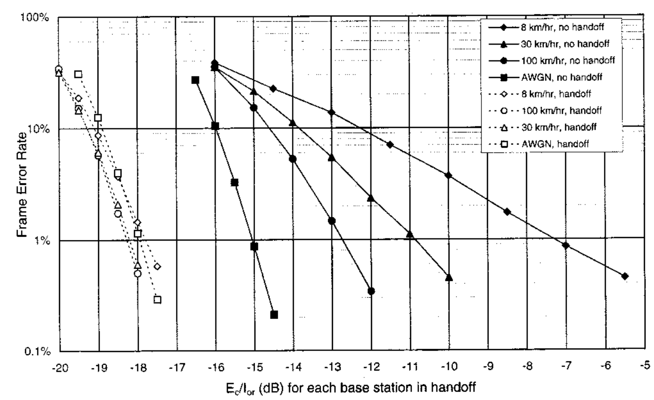

Fig. 13. 8-dB plot. Two paths per BS. Forward-link simulation results (rate set 1: 9600 b/s). HO versus no HO, one path per BS, per path $\hat{I}_{\rm or}/N_0 = 10$ dB.

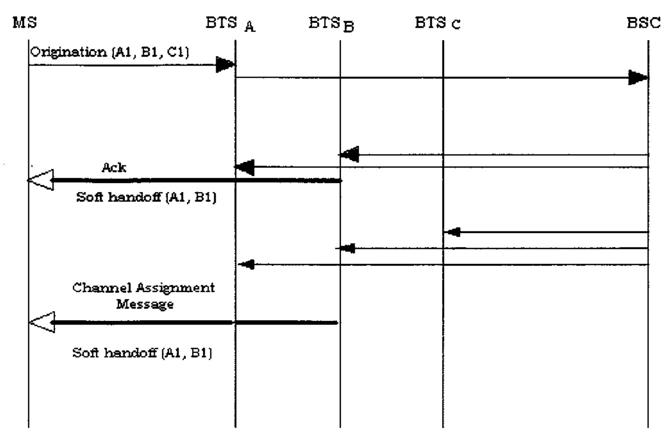

Fig. 14. Illustration of call origination.

of the neighboring BS. The remaining gain comes from the additional diversity on the forward link.

VIII. F-CCCH OPERATION

To show the operation of the F-CCCH, we use a call origination as shown in Fig. 14. It uses the BS's and the various flags previously described. It is assumed that SHO is permitted on the F-CCCH between BTS's. The MS sends the OM while located in sector A1 of the corresponding BTS. Two additional BS's have pilots strong enough to combine: B1 and C1. The flags that the MS receives in the overhead messages indicate that SHO is permitted with B1 and that Access HO is permitted with C1. The OM is received at a BTS and forwarded to the BSC. At the BSC, the message is processed. The layer-2 fields and the PMI are stripped from the message. At the BSC, an acknowledgment (R_ACH) is generated and sent to the BTS's for transmission to the MS on the F-CCCH. The BTS's selected to be sent the message are those corresponding to pilots reported to be strong by the MS and have CCS set to one. The BSC sends the layer-2 acknowledgment to these BTS's and these BTS's send the layer-2 acknowledgment to the MS in SHO. In the example, the MS reports B1 and C1 to have strong pilots, and since CCS set to one in B1, the BSC sends the acknowledgment to BTS B and A1.

After setting up the channel, the BSC then sends the CAM (or information to determine the CAM) to BTS's A, B, and C. The BSC includes BTS B since B1 was reported by the MS, and CCS was set to one. The BSC includes BTS C since C1 was reported and ACS was set to one. The CAM is transmitted in SHO mode from BS's A1 and B1. As in IS-95-B, the CAM is also transmitted from BS C1. This transmission does not have to be in a SHO mode since the MS is not combining the transmission with the transmissions from other BS's. While this has been shown for an origination, the same methods work for all other exchanges, which are begun by the MS. It is evident that the BSC can save the last set of PMI information reported by the MS. The BS can send a message directly to the MS by transmitting the message in these BS's and using SHO for those in which CCS is set to one.

IX. F-CCCH SHO Operation for Synchronized BTS's

In receiving either the acknowledgment (ACK) or the CAM on the F-CCCH, the MS would diversity combine the signals from the BS's in SHO, just as is done on the traffic channel when the MS is in SHO. In order for diversity combining to work correctly, all of the BTS's must send out information at the same time. In IS-95, this is done on the traffic channel by having all of the forward-link frames time synchronized in their transmission. This is relatively straightforward since the traffic channel is a dedicated channel and no specific control is required. However, this is more complicated for a common channel scenario than for a dedicated scenario, as with the traffic channel. In this case, there can be messages that need to be transmitted in different cells. For example, message 1 might need to be transmitted in sectors $\{\mathrm{BTS}_{\mathrm{A1}}, \mathrm{BTS}_{\mathrm{A2}}, \mathrm{BTS}_{\mathrm{B1}}\}$ and message 2 might need to be transmitted in sectors $\{\mathrm{BTS}_{\mathrm{A1}}, \mathrm{BTS}_{\mathrm{A2}}, \mathrm{BTS}_{\mathrm{C1}}\}$. As a result, the BSC would typically be required to perform a scheduling algorithm so that the single channel transmitted by each BS is appropriately used. This is not too difficult if the F-CCCH is not heavily loaded. Fig. 15 illustrates the timing.

It should be noted that either these messages must all be transmitted at the same time. A straightforward approach would be to have the BSC use some centralized algorithm that schedules the forward-link transmission for all BTS's that are in SHO as set by the CCS flag. As noted before, only sectors of a BTS may be in SHO, thus permitting the F-CCCH from all sectors of a BTS to be in SHO.

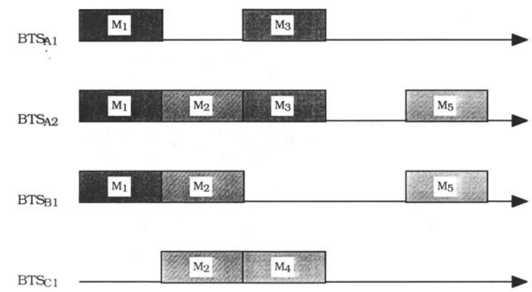

Fig. 15. Illustration of F-CCCH messages for synchronous BS's.

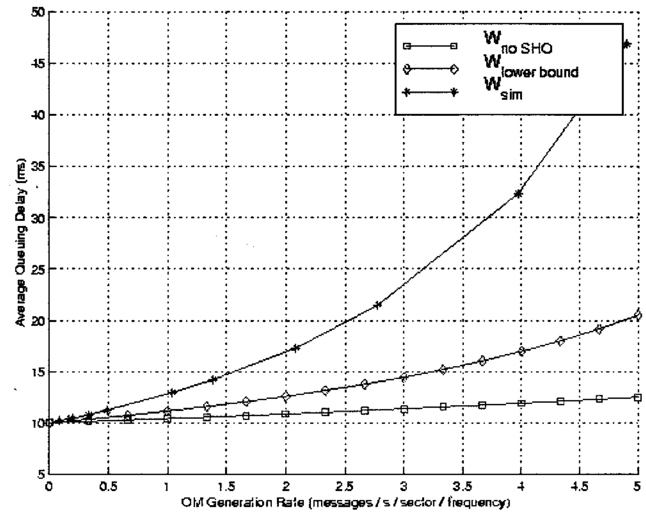

Fig. 16. Delay analysis.

A. Delay Analysis

One important issue to analyze is the BS throughput for the SHO case for the IS-95-A/B and proposed cdma2000 mode. Assume the following model: the system consists of 40 cells, three sectors/cell. Thus, 120 sectors handled by a BSC. For each OM message received, the BSC must send an ACK and a CAM on the F-CCCH, in SHO among the sectors reported in the OM. Only one ACK or CAM message can be transmitted in one 20-ms slot of the F-CCCH of a given sector. The OM messages are generated according to a Poisson process with a rate of λ messages/sec/sector/frequency. Using Little's formula $(N = \lambda T)$, if we assume 40 Erlangs of traffic per sector per frequency, and an average call duration (T) of 120 s, we get $\lambda = 1/3$ call setups per sec per sector per frequency. The operating point is thus assumed to be $\lambda = 1/3$. The average waiting delay W represents the queuing delay at the BSC from when an OM is received at the BSC and until an ACK/CAM is transmitted.

If the transmissions is from only one BS, i.e., an IS-95A system, the performance can be obtained using an M/D/1 queue (see [14]), and for the operating point of $\lambda = 1/3$, $W = 10.14$ ms is the average queueing delay. For unsynchronized transmissions from multiple BS's, i.e., the IS-95B case, an analysis for $\lambda = 0.33$ gives $W = 10.35$ ms [15]. For synchronized transmissions from multiple BS's, i.e., for SHO in cdma2000, the ACK/CAM message must be

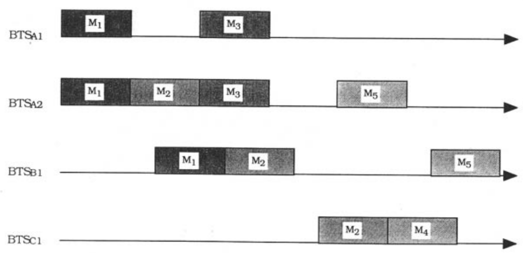

Fig. 17. Illustration of F-CCCH messages for asynchronous BS's.

transmitted simultaneously on the F-CCCH of all the sectors identified for SHO in the OM message. For example, when an ACK/CAM to be sent in SHO by sectors i and j is waiting in the queue, and sector i has nothing to transmit in the next slot, but if sector j has some other message waiting in queue ahead of this ACK/CAM, then this ACK/CAM cannot be transmitted in the next slot. Fig. 16 shows the average queuing delay (in milliseconds) versus the OM generation rate (in messages/second/sector/frequency). The delays shown are the average queueing delay when F-CCCH is in HHO, the delay when messages are sent by multiple BS's asynchronously is a lower bound on average queuing delay when F-CCCH is in SHO, and the average queuing delay measured via simulation when the messages are sent in SHO, i.e., synchronous transmission. These three cases are respectfully referred to as W_{noSHO}, $W_{\mathrm{lowerbound}}$, and W_{sim} in Fig. 16.

B. F-CCCH SHO Operation for Asynchronous BTS's

It should be noted that the above process also works for asynchronous BS's. Asynchronous BS's are those in which the timing is not necessarily aligned between them. For example, the frame is offset from one BTS to another. Asynchronous BS's, as in wide-band CDMA (WCDMA), adds a complexity in that the MS must deskew before combining the transmissions from multiple BTS's. Fig. 17 illustrates the timing for a system in which $\mathrm{BTS_{A1}}$ and $\mathrm{BTS_{A2}}$ are synchronized and $\mathrm{BTS_{B1}}$ and $\mathrm{BTS_{B2}}$ are not synchronized. The messaging is the same as in Fig. 15. Note that for asynchronous BS's, the relative timing on each channel is maintained; however, one channel is skewed relative to another channel.

This can be implemented by the MS in the following way. The MS has maintains a deinterleaver buffer whose length is the maximum amount of skew between the BTS's. The MS is assumed to know the timing offset of the various BTS's, perhaps as obtained by synchronization patterns, which are embedded in the forward links of these BTS's. As the MS receives a symbol from a particular BTS, the MS does the normal receiver processing functions such as despreading, removing the orthogonal cover, and demodulation in each of its Rake receiver fingers [8]. The difference occurs in the deinterleaving. Here, the output of every Rake receiver finger which corresponds to a different BTS must be separately deinterleaved. In particular, assume the above example with the MS receiving from $\mathrm{BTS_{A1}}$, $\mathrm{BTS_{A2}}$, and $\mathrm{BTS_{B1}}$. Assume that there are four Rake receiver fingers with two fingers being assigned for different multipaths from $\mathrm{BTS_{A1}}$ and the remaining two fingers being assigned to $\mathrm{BTS_{A2}}$, and $\mathrm{BTS_{B1}}$. The MS combines the signal from the two RAKE fingers from $\mathrm{BTS_{A1}}$ as it normally does. As a result there are three remaining streams, one from each BTS ($\mathrm{BTS_{A1}}$, $\mathrm{BTS_{A2}}$, and $\mathrm{BTS_{B1}}$). The next step is the actual deinterleaving. The MS takes a symbols from the first arriving BTS and places it in the deinterleaver buffer. When the corresponding symbol arrives from the second BTS (the one having timing later than the first BTS), the MS takes the symbol from the deinterleaver buffer, combines it with the newly arriving symbol, and replaces the symbol into the deinterleaver buffer. When the corresponding symbol arrives from the third BTS (the one having timing later than the second BTS), the MS takes the symbol from the deinterleaver buffer, combines it with the newly arriving symbol, and replaces the symbol into the deinterleaver buffer. When all the symbols have been placed into the deinterleaver buffer from all BTS's, the MS performs the deinterleaving and then the decoding. It should be noted that the MS can attempt the decoding before it has received the symbols from all BTS's. It should also be noted that the MS may require a second deinterleaver buffer to begin buffering received symbols from the next interleaved frame before symbols have been completely received from the previous interleaved frame.

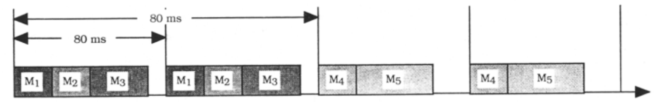

Fig. 18. Illustration of F-BCCH messages for asynchronous BS's—I.

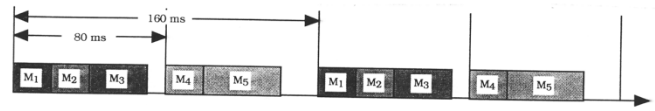

Fig. 19. Illustration of F-BCCH messages for asynchronous BS's—II.

X. Broadcast Channel

The F-BCCH is a separate logical channel conveying overhead information. It is not transmitted in a SHO mode since much of the information conveyed is specific to a sector. The F-BCCH can also be operated in an intermittent mode similar to the F-CCCH. However, the F-BCCH only conveys a few overhead messages that do not change frequently. Essentially, only MS's, which are first powering on or which are handing off to the sector, need to receive the overhead messages. Thus, it is desired that the F-BCCH be transmitted with as little an amount of power as is necessary, e.g., the overhead messages can be transmitted and then repeated. This is shown in Fig. 18. In the F-BCCH, the messages are repeated at known intervals in a way that the transmitted symbols are exactly the same.

Fig. 18 shows that messages are repeated once 80 ms later. It should be noted that this time interval could be any value that is known by the MS (or told to the MS). Furthermore, it should be noted that message transmissions could be interleaved with old message transmissions, as is shown in Fig. 19. The main

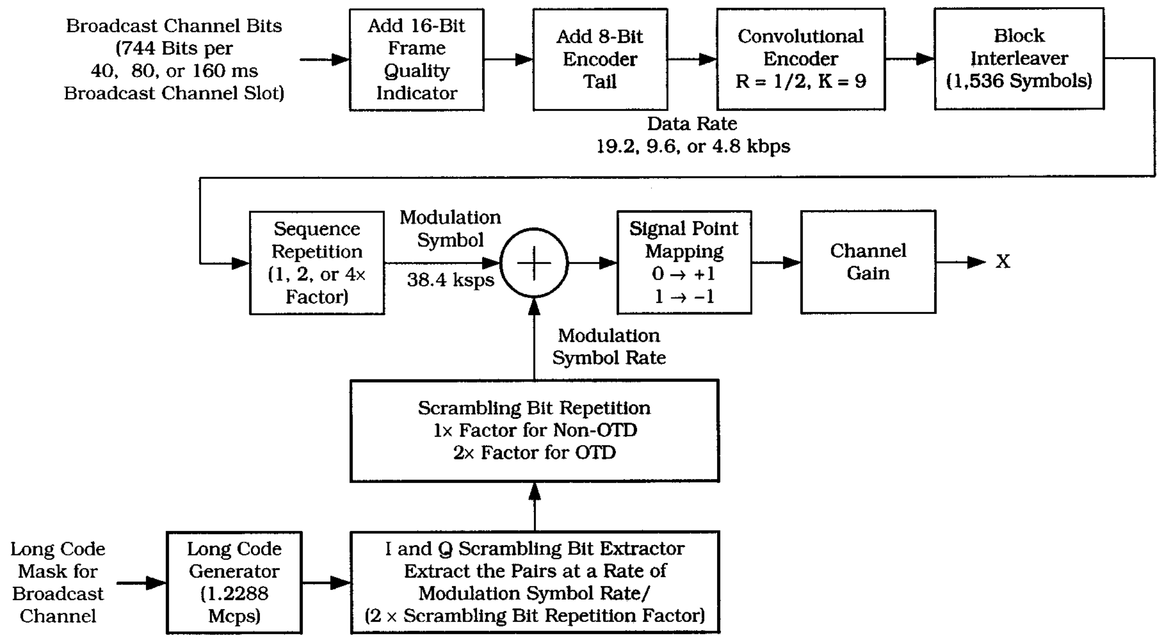

Fig. 20. Generation of F-BCCH.

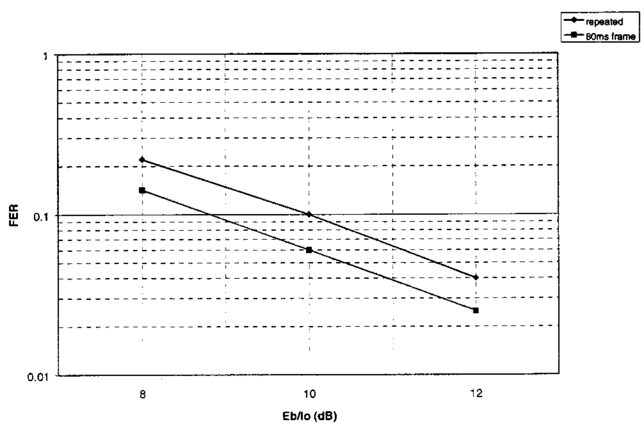

Fig. 21. Performance of F-BCCH (5 km/h).

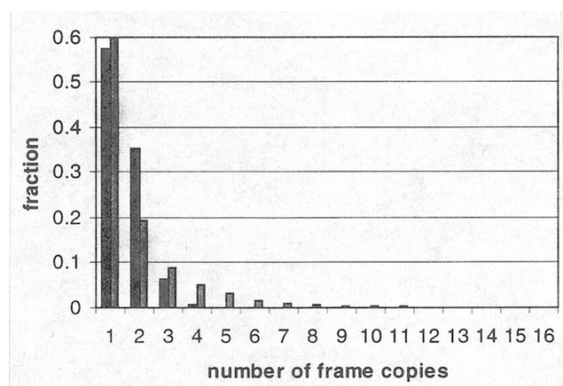

Fig. 22. Soft combining in F-BCCH ($Eb/No = 4$ dB, 5 km/h).

requirement being that the message is repeated at some interval known to the MS so that it can perform diversity combining.

A. F-BCCH Channel Structure

The F-BCCH channel is generated according to Fig. 20.

Performance results are shown for one-path classic Rayleigh fading at 1960 MHz for a data rate of 9600 b/s. The code used is a convolution code with $R = 1/2$, $K = 9, 8$ tail bits, and BPSK modulation. An 80-ms interleaver of size is 128 × 12 is used. Fig. 21 shows the frame error rate (FER) versus the SNR.

Simulations have been carried out and, at 30 km/hr, the performance is about the same. Fig. 22 shows the performance when the MS decodes each transmitted 80 frame independently (without soft combining) and with soft combining. The left-most curve is with soft combining, and the other without. The term fraction refers to the fraction of frames that are correctly decoded at the given iteration.

TABLE V
PROBABILITY OF CORRECT RECEIPT AFTER SECOND SET OF TRANSMISSIONS

v	$\frac{E_b}{N_0}$	P_{NC}	P_C	$\frac{E_b}{N_0}$	P_{NC}	P_C
5	4	.956	.995	1	.920	.999
30	4	.907	1.000	1	.363	1.000
5	7	1.000	1.000	4	.991	1.000
30	7	1.000	1.000	4	.995	1.000

The probability that a message is correctly received after 160 ms (two frames with the 80-ms interleaver or four frames with the 40-ms interleaver) frames is given in Table V. The BS transmit power is the same for each row of the table. The velocity v is in kilometers per hour. The next three rows characterize a 9600-b/s channel with 80-ms interleaver, and the last three rows refer to a 19200-b/s channel with 40-ms interleaver. The (E_b/N_0)'s are in decibels, $P_{\rm NC}$ refers to the probability of correct detection with no combining, and P_C refers to the probability of correct detection with soft combining.

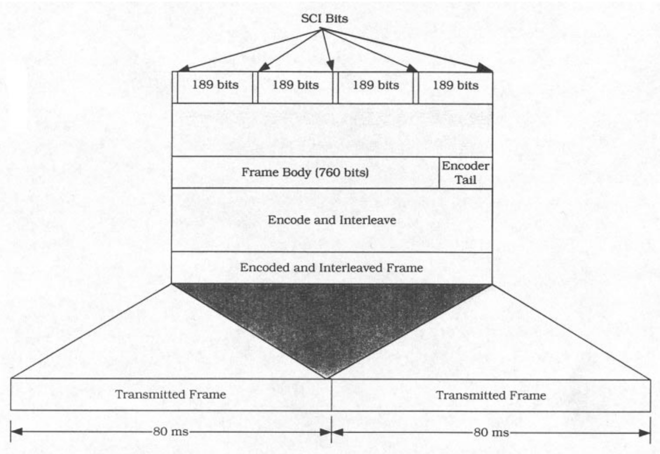

Fig. 23. F-BCCH frame structure.

The required $E_c/I_{\rm or}$ for the F-BCCH at the edge of cell is 17 dB and 14 dB for a 4-dB E_b/N_0 at 9600 b/s (1 dB at 19200 b/s); the required $E_c/I_{\rm or}$ for the F-BCCH at the edge of the cell is equal to 14 dB for a 7-dB E_b/N_0 at 9600 b/s (4 dB at 19200 b/s), respectively.

Thus, the proposed F-BCCH structure performs well using a 19200-b/s transmission rate with a 40-ms interleaver. It provides both lower delay and higher reliability than the 9600-b/s transmission rate with an 80-ms interleaver. This is at the expense of requiring 1/64th of the orthogonal function space versus 1/128th of the orthogonal function space on the forward link.

B. Design of F-BCCH

The F-BCCH is split into intervals of 40 ms (see Fig. 23). Each 40-ms period is immediately repeated three times to provide diversity. There are at most 768 bits per frame, and permits all the messages to be repeated every 320 ms. The most needed message, the extended access parameters message, is sent every 80 ms. The global service redirection message is infrequently sent as it is rarely used, except for beacon cells and cells that are being installed or tested.

If the MS does not receive the overhead messages within the 160-ms frames, then the MS will attempt to receive the messages the next time they are repeated. Assuming that the channel is independent at this later time, the MS does not perform soft combining between the first and the second set of transmissions due to memory constraints at the MS, and would constrain the upper layers to repeat the messages exactly, adding considerable complexity. Given the messaging described above, the second set of transmissions would begin 160 ms after the end of transmission of the first set of messages.

Performance results are shown for a one-path classic Rayleigh fading at 1960 MHz for data rate 19200 b/s. The code used is a convolution code with $R = 1/2$, $K = 9, 8$ tail bits, and BPSK modulation. The probability that a message is correctly received after 160 ms (four frames with the 40-ms interleaver) frames is given in Table VI. The BS transmit power is the same for each row of the table. The velocity v is in kilometers per hour. The table shows the probability of correct decoding after the first and second set of transmissions for a 19200-b/s channel with 40-ms interleaver. The E_b/N_0's are in decibels, P_1 refers to the probability of correct detection after the first transmission, and P_2 refers to the probability of correct detection after the second set of transmissions. Note that soft combining is done to benefit from the diversity gains in each frame.

TABLE VI
FRAME ERRORS—TWO TRANSMISSIONS

v	$\frac{E_b}{N_0}$	P_1	P_2
5	1	0.964	.999
30	1	0.997	1.000
5	4	0.9995	1.000
30	4	1.000	1.000

Thus, the given structure performs quite well, and has a low delay. However, note that the messages sent on the F-BCCH can change, albeit infrequently. When it does change though, it implies that the MS must reconfigure parameters to be able to communicate with it. However, this implies that the mobile has to keep monitoring the F-BCCH of every BS in its active set very often. This is power consuming, and has a bad effect on the battery life of the MS, which can be mitigated by the technique described in Section V.

XI. OVERALL CHANNEL STRUCTURE

The F-CCCH is transmitted intermittently. As a result, a preferable arrangement is for it to be variable rate/on–off. In this arrangement, the channel is transmitted for a frame if there is a message to send, as shown in Fig. 4. Thus, no capacity is wasted in transmitting this channel when there is no message to send. As was previously indicated, the channel can be transmitted at the power level that is required in order to convey information with the MS. Thus, BS power (and, thus, capacity) is not wasted by sending at too high a power level. The F-CCCH can be transmitted at different rates, as has been shown in [6] on the F-DCCH. Thus, the BS can adjust both the power level and transmission rate in order to optimally select the method in which to communicate with the MS. It should be noted that adjusting the transmission rate requires that the MS be able to demodulate different rates by using methods in which the MS automatically determines the rate by just examining the data. The transmission rate can also be conveyed to the MS by using auxiliary rate information, which is transmitted in a separate signaling path.

A. Standby-Time Comparison

To get a reasonable estimate of the standby time of the phone, we make the following assumptions. Consider no coverage holes, registration transmits as included in talking budget, everyone using the same type of phone and battery for comparison purposes, and the phone being left on for 24 h a day. In a two-state battery consumption model, battery life is broken down into talk time (TT) and standby time. Let f_t be the fraction of time using TT, f_s be the fraction of time using standby time and UT be the utility time of phone. Then, ${\rm UT} = 1/((f_s/{\rm ST}) + (f_t/{\rm TT}))$. If the standby time was unlimited, we could define the asymptotic case as a limit ${\rm UT}_\infty = \lim_{{\rm ST}\to\infty} {\rm UT} = {\rm TT}/f_t$. The target standby time (τ)

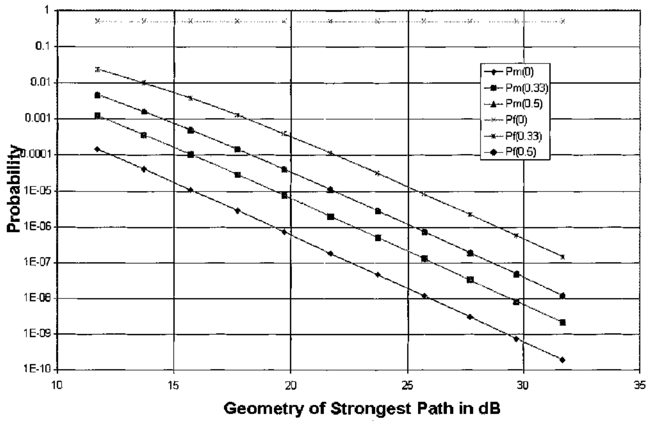

Fig. 24. Standby-time improvement.

achieves an utility time of 90% of the asymptotic value. For a heavy user (120 min/day), $\tau = 198$ h. For a medium user (25 min/day), $\tau = 1019$ h, and for a light user (5 min/day), $\tau = 5166$ h. Hence, improvements of up to 1020 h of standby time per 2 h of TT are very useful to the customer. The utility times for the heavy, medium, and light user would be 0.98, 4.32 and 15.4 days, respectively.

To provide a comparison, consider eight pages per 80-ms slot. Assume 5-ms warm-up time, and a cost of 54 ms to monitor full paging slot. Using the present design at 4800 b/s, the amount of improvement depends on hardware platform. Define α as in Section V. Presently, for many commercially available phones, a value of $\alpha = 10$–40 is common. This may go up considerably in the near future.

Fig. 24 summarizes the results. In Fig. 24, the y-axis represents the percentage improvements in the phone standby time with the F-QPCH over the IS-95-based systems. SCI was defined at the conclusion of Section III-A.

XII. Conclusion

The design discussed in this paper allows for seamless interoperability between all combinations of BS's and MS's that do and do not support this new feature. It does not significantly impact call setup time or increase the missed page probability. However, it greatly reduces the amount of time the phone spends monitoring the slots of the paging channel. The introduction of SHO allows the message to be transmitted at lower power levels. This significantly reduces the interference to the other mobiles, and especially leads to a far better performance on the cell boundaries, where the problem of call drops is most acute.

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