Lucent Technologies
Bell Labs Innovations

subject: **CME 900 MHz Cordless Phone Software Functional Description: Frequency Hopping Spread Spectrum Telephone Platform**

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INTERNAL MEMORANDUM

1 Introduction

This document describes the principles and software functionality used in CME's frequency hopping spread spectrum (FHSS) telephone platform. Only aspects of the communications link layer of the FHSS phone are discussed. It is assumed the reader has reviewed the software documentation associated with CME's low-power narrowband telephone platform.

2 Overview

The software architecture of the FHSS telephone platform differs with that of the narrowband phone platform in primarily three respects:

1) Frequency hopping and swapping, in which the radio frequency (RF) channel is changed each 5 ms time-division duplex (TDD) period and poor (noisy) channels are replaced with clear channels during the course of a call.
2) FCC-compliant link acquisition, in which the handset and base initiate a link within the time-bandwidth restrictions imposed by the Federal Communications Commission (FCC).
3) RF power control, in which the RF output power of the transmitter is adjusted as a function of RF conditions in an attempt to maintain clear communications while minimizing power consumption.

These subjects are addressed in detail in the sections that follow. The registration function, which also differs between the FHSS and narrowband platforms, is covered in separate documentation.

3 Frequency Hopping

During the course of a communications link between the handset and base, the FHSS phone changes its radio frequency each RF-frame period, or TDD period, which is 5 ms for our architecture. This process is called frequency hopping, and the hop table contains a list of the frequencies cyclically (periodically) accessed for hopping. During the course of a link, a given frequency may experience interference such that communication is impossible during the time that the base and handset transceivers are tuned to that frequency. In such cases, the handset and base will agree to remove the offending frequency and replace it with a (potentially) clear frequency from a pool of yet unused frequencies. This process is called swapping.

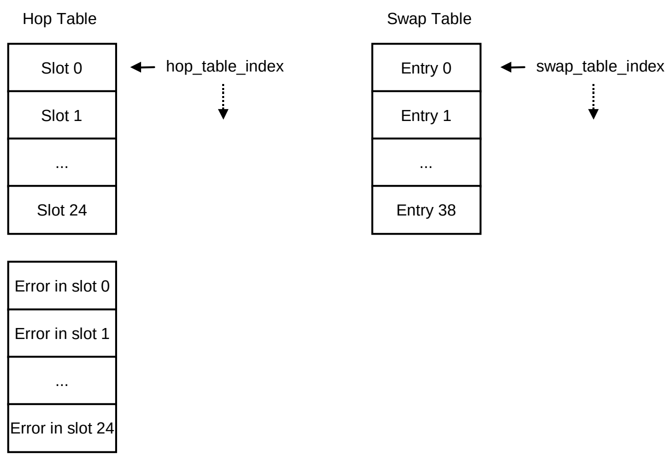

Figure 1. Hop and Swap Tables. The base and handset each have a copy of the hop table. Only the handset, as master, maintains the slot-error table and the swap table.

3.1 Hop and Swap Tables

The characteristics of hopping are specified, in part, by FCC Part 15. For our design, hopping must be performed over a table of at least 25 frequencies arranged in pseudo-random order. Because the hop table is indexed cyclically over time during a link, the period of the hop table is therefore 125 ms ([5 ms/channel-frame] * [25 channels]).

In our design, the 902–928 MHz band is divided into 64 nonoverlapping channels linearly arranged from the bottom to the top of the band. When the base and handset register with one another, the security code used to recognize one another in RF-space is also used to generate the hop table. The security code is used as a seed to a pseudo-random number which in turn is used to produce a randomly ordered list of the 64 integers, or 64 channel numbers, in the range [0, 63]. The first 25 entries in the list are used as the hop table. Each entry in the hop table is called a slot. Slot-0 contains the first channel in the hop table, slot-1 the second channel, and so on up to slot-24. This is illustrated in Fig. 1.

The remaining 39 (64 – 25) entries in the list comprise the swap table and acquisition channel, as shown in Fig. 1. These channels are potentially clear frequencies that can be exchanged with slots in the hop table should one or more slots contain a frequency over which communications are poor. The 39th entry of the swap table is also used as the acquisition channel. The acquisition channel is a fixed channel (changed only at registration) over which the handset and base establish a link, for example, when the handset is in the sleep state and the user wishes to make a call. By convention (FCC), the acquisition channel must be available to the swap table. It is placed at the end of the table to satisfy transmission-compliance requirements. This subject is discussed further in the section on link acquisition .

While both the handset and base maintain their own copy of the hop table, only the handset maintains a copy of the swap table and slot-error table. This is discussed further in the next section.

Whenever the base and handset establish a link, for example when Phone-On is pressed, the base and handset re-initialize their hop tables to that generated from the security code used as the initial seed. This way, link acquisition is successful even if, for example, the handset battery has been recently replaced.

3.2 Swap Algorithm

3.2.1 Slot error table

RF communications degrade or fail under two conditions: insufficient signal strength, as would occur when the handset is out-of-range; and interference, as would occur if another nearby RF appliance is using the same frequency(ies) of

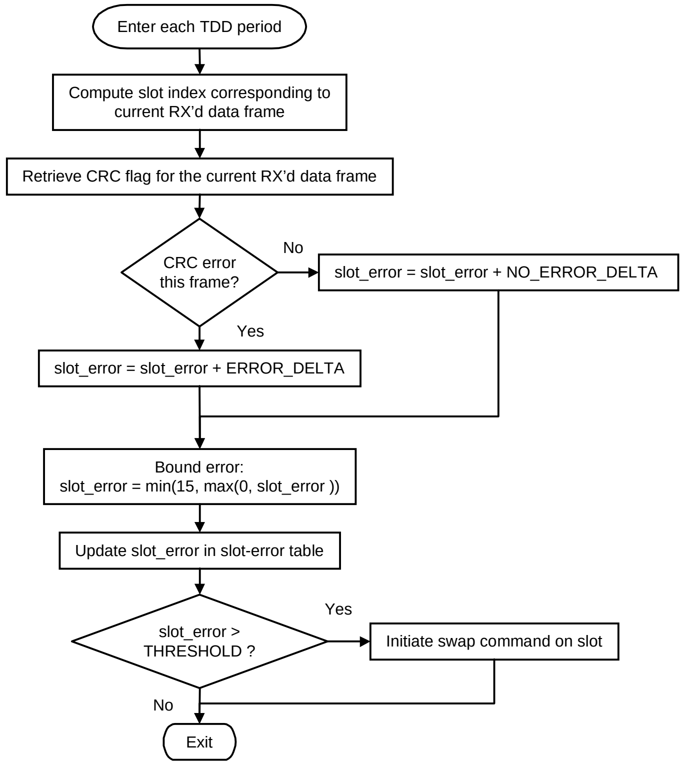

Figure 2. Slot-Error Update Algorithm.

communications. When the handset is out-of-range, communications across all channels in the hop table fails. No swapping will occur because no channels exist over which the base and handset can exchange commands to initiate a channel swap. When the handset is within range but is in the presence of one or more interferers, communications on only some channels is degraded. In this case the handset and base can successfully exchange commands to initiate a swap of the slots experiencing poor communications.

The handset serves as the master in the swapping process. Fig. 2 shows a flowchart of the slot-error update algorithm. A slot for which communications are poor will experience errors in the form of failures of the cyclical redundancy check (CRC) for the data exchanged during RF transmissions performed over the frequency contained in that slot. The handset maintains an integer-valued error metric for each of the 25 slots of the hop table. Each TDD period, the handset checks the CRC flag of the data frame it received from the base. If the data are received without error, the error measure for the slot number corresponding to the received data is decremented by the quantity NO_ERROR_DELTA. If after being decrement the error is negative, the error is set equal to zero. If the received data are in error, the error measure for the slot is incremented by the value ERROR_DELTA. Thus, if a given slot is experiencing no errors its error metric equals zero, and the measure is greater than zero if the slot is experiencing errors.

In the current implementation the ERROR_DELTA = 9 and the NO_ERROR_DELTA = 1. The resulting error is then compared to a threshold and, if the error equals or exceeds the threshold, a swapping process is initiated for that slot. With the current threshold set to 10 (THRESHOLD = 10 in the flowchart), a swap is initiated on any slot for which 2 or more CRC errors are experienced within any 10 consecutive visits to that slot. Thus, a swap is initiated for a slot if it experiences two consecutive erroneous frames or two erroneous frames separated by up to 8 good frames.

3.2.2 Swap procedure

When the handset determines a slot should undergo swapping it initiates the swap command protocol. The handset does so for the first slot whose error measure exceeds the threshold test described above.

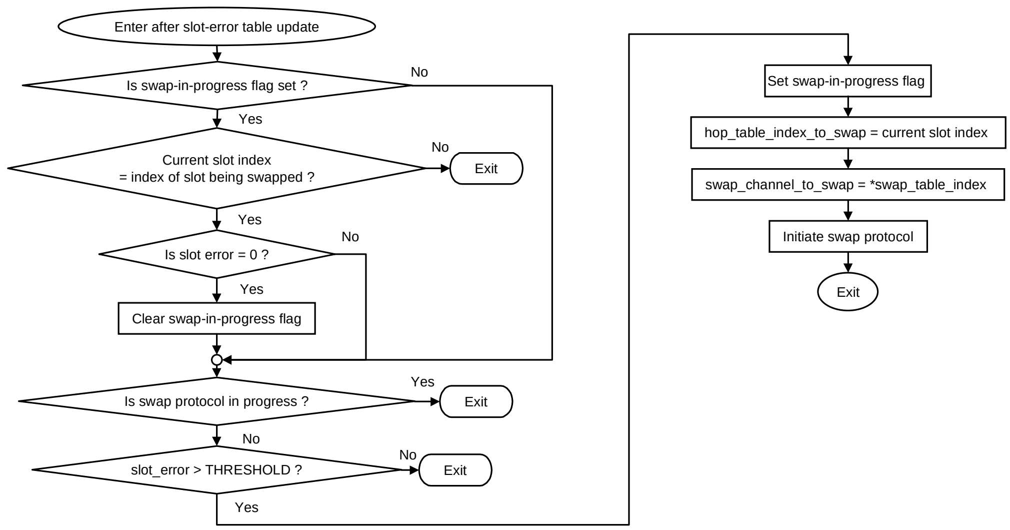

Figure 3. Swap Algorithm.

The swap process adheres to these two rules:

1) When a slot is chosen for swapping, the swapping of other slots is inhibited until the command protocol for swapping that slot successfully completes.
2) A swapped slot undergoes re-swapping until communications in that slot are clean.

Because the swap protocol is carried out over potentially many TDD frame periods, it is common in poor conditions that other slots will achieve an error measure that also exceeds threshold. Subsequent swaps are only initiated once the slot undergoing swapping is successfully swapped. This means the protocol of the swap for the first slot must complete successfully and communications over the slot must improve as a result of the slot. If communications do not improve after the swap is complete, as would occur if the new frequency from the swap table is also noisy, swapping is reinitiated on that same slot using the next available frequency in the swap table.

Fig. 3 shows a flowchart of the swap update algorithm, which implements the principles in 1) and 2) above. The algorithm is executed immediately following the slot-error table update routine. At the initiation of a swap, just after the threshold test, the handset saves the slot number of the hop table being swapped (hop_table_index_to_swap) and saves the current entry (channel number) pointed to by the swap table index pointer (swap_channel_to_swap). A flag is set to initiate the swap command protocol, which will begin at the next TDD period. The handset's swap command transmits the hop_table_index_to_swap and the swap_channel_to_swap to the base using a separate command type for each. Once the base acknowledges receipt of both parameters, the base and handset agree to actually implement the swap at the next frame-clock boundary (25 TDD periods following the base's acknowledgment of the second parameter.

It is possible that the base acts on a swap command but the handset does not. This is because the handset may not receive the base's acknowledgement of the second parameter, a situation that can occur if the handset has nearby interference or at end-of-range when communications are poor over the majority of channels in the hop table. Fortunately, the swap algorithm is self-correcting in the sense that it will eventually correct any "divergence" in the base and handset hop tables. When a slot is mismatched, each frame the handset receives in that slot will be in error because the base and handset will be using different frequencies. Consequently, just after the mismatch occurs the slot error measure will not improve and the swap algorithm will continue to swap the slot. Eventually, if communication conditions permit, the slot will be successfully swapped. Note that rule 2) above insures that the base and handset hop tables can differ in no more than one slot at any given time.

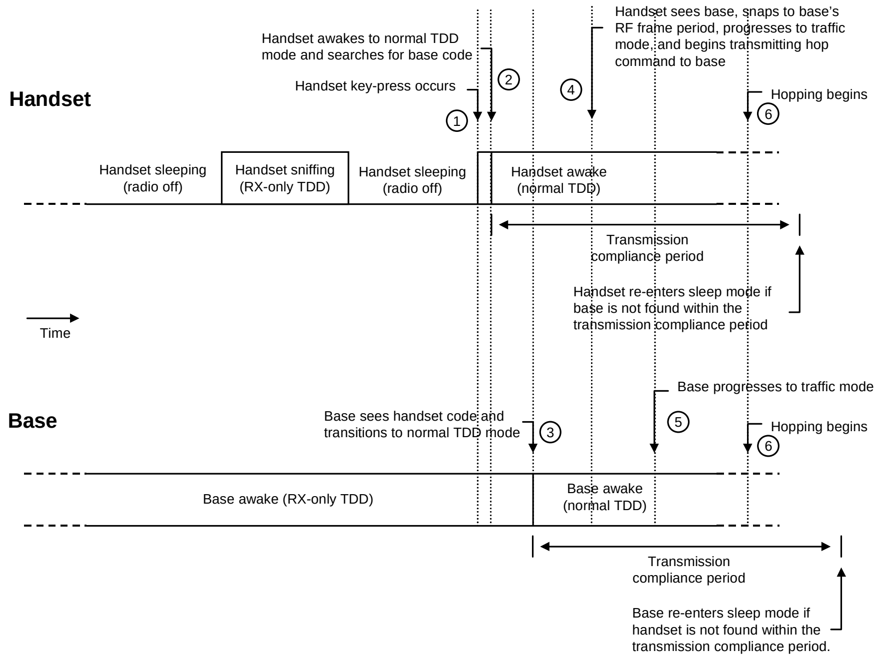

Figure 4. Handset-Initiated Link Acquisition.

4 Link Acquisition

Link acquisition is the process of building a sustained, two-way communications link between handset and base when no link is in progress. There are two starting points from which acquisition is initiated: handset-initiated acquisition, in which the handset signals the base that it wishes to form a link, and base-initiated acquisition, in which the base instigates the link.

Link acquisition always proceeds from the sleep and sniff states of the base-handset pair. When the base and handset are not linked, the base remains in a constant receive-only state, called sniff, while the handset periodically transitions between a dead-stop, or sleep, state and the sniff state. When sniffing, both the handset and base use a receive-only TDD frame structure, which is just the normal TDD frame structure with the TX portion replaced by an extended idle (PLL settling) period. In the sniff state, and during the process of acquisition, the base and handset radios are programmed to the same channel frequency. This channel is called the acquisition channel.

While the base may stay "awake" indefinitely, the handset must sleep in order to conserve battery power. This asymmetry in sleep-sniff operation results in some differences in the protocol of link acquisition, depending on which side initiates the link. The protocol for handset-initiated acquisition is the simpler of the two and is discussed first.

4.1 Handset-Initiated acquisition

Figure 4 shows a timeline of the handset-initiated link acquisition process. Steps 1 through 5 identified in the figure comprise the more salient components of the link-building process and are discussed in detail below. Note that these steps are identical to those performed by the narrowband telephone platform. In this direction of acquisition the FHSS telephone differs from the narrowband phone only in that frequency hopping is initiated following successful acquisition. Also, the FHSS platform must limit the duration over which it attempts acquisition (because the base and handset are transmitting on the signal acquisition channel at high power). This latter subject is discussed in the section entitled Failed Acquisition Procedure.

4.1.1 Step 1

As shown in the figure, the handset is awakes in step 1 as the result of the user pressing a key on the keypad. Prior to this, the handset is in sleep mode. In sleep, the handset's radio is off, the CSP1009 is stopped (oscillator is disabled), and the DSP's core clock is stopped. In addition, the DSP's IOP connection to the keypad is programmed to re-start the core clock in the event of a key-press. Following the key-press the DSP's core clock is re-started and the handset jumps immediately to the acquisition function. If instead of sleep the handset had been executing its sniff cycle when the keypress occurred, the handset would also jump to the acquisition function.

4.1.2 Step 2

The handset programs its RF frame to the normal TDD mode and begins executing its acquisition function. The handset transmits a partial data frame consisting of the synchronization code and security code (the remaining fields of the transmitted frame are written with the preamble sequence). The handset continually slips the time reference of its TDD period while analyzing the received data for the synchronization word from the base. Following each such slip, the handset remains at the current time reference for 3 TDD periods (15 ms). If the handset sees the base's synchronization code at any location in its 304-bit received frame and in any two consecutive TDD periods, the handset transitions to the traffic function and proceeds establish communications with the base. If at the current time reference the handset does not find the synchronization code, it slips its time reference and continues the search at the new reference point.

4.1.3 Step 3

While the handset is searching for the base's code it slips the time reference of its TDD period. Because the handset is also transmitting the synchronization code, the handset’s transmit period will eventually overlap with the receive portion of the base's RF frame. Recall that, when not communicating with the handset, the base is programmed in an RX-only TDD mode and is constantly analyzing received data for the handset's code.

When the base sees the handset's code in any two consecutive TDD periods it transitions to a normal TDD RF frame and begins executing its acquisition function. The base transmits a partial data frame consisting of the synchronization and security codes (the remaining fields of the transmitted frame are written with the preamble sequence).

4.1.4 Step 4

The handset continues to slip its time reference and eventually detects the base’s synchronization code. Having seen two successive frames with the base’s code, the handset will adjust, or snap, the time reference of its TDD period to exactly match that of the base. The handset transitions to traffic mode, in which it will establish a communications link with the base and exchange both speech and command data.

4.1.5 Step 5

With the handset aligned to the base’s TDD period, the base necessarily detects the handset’s synchronization code in the expected position of the base’s received frame. Seeing two consecutive frames with the handset’s code, the base transitions to traffic mode.

4.1.6 Step 6

When the base and handset have established communications with one another the base sends a command to the handset instructing the handset to reset its frame-clock, which counts successions of 25 TDD frames. Having received the reset command from the base, the handset constructs a command to instruct the base to begin frequency hopping and pushes this command onto the handset’s buffer of transmitted commands. The handset’s command processor repeatedly transmits the command until the base acknowledges receipt. Frequency hopping will commence at the next frame-clock boundary, which for the FHSS platform is 25 frames after the base first acknowledges receipt of the handset’s command to initiate hopping.

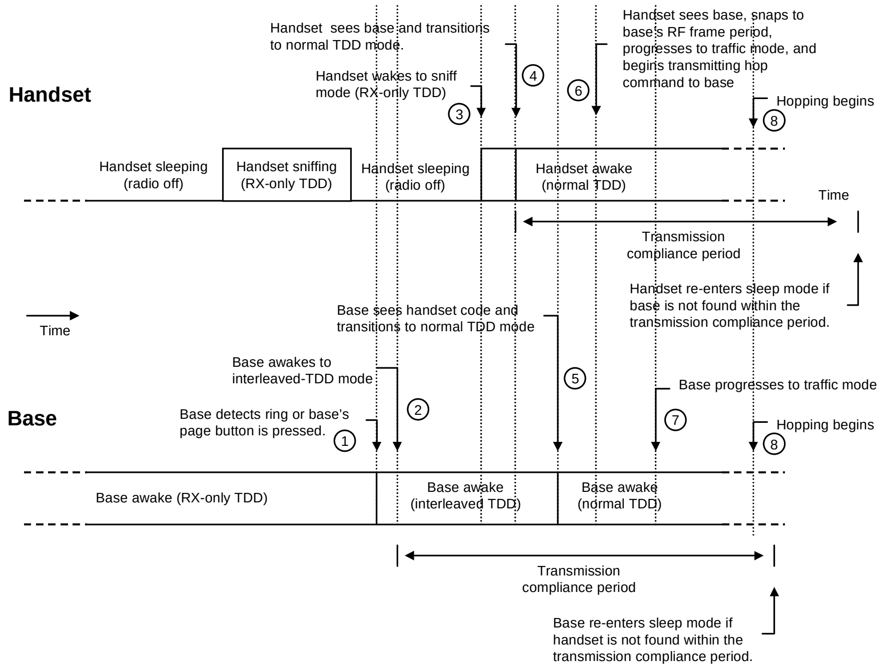

Figure 5. Base-Initiated Link Acquisition.

4.2 Base-Initiated Acquisition

Figure 5 shows a timeline for the base-initiated link-acquisition process. The base will initiate a link with the handset when the base detects an incoming call (valid ring signal) and when the base's page button is pressed to locate the handset. Eight steps are identified in Fig. 5 for this direction of acquisition. Though some of these steps are common to those executed by the narrowband telephone, the FHSS telephone does differ from the narrowband phone in the manner that base-initiated acquisition is performed. These differences are clarified in a separate section below.

4.2.1 Step 1

When the base and handset are not communicating the base is fixed in a receive-only TDD mode in which it is constantly scanning the acquisition channel for the handset's synchronization code. When a ring signal, page-button event, or other base-local event requiring a link with the handset occurs, the base exits the receive-only TDD mode and begins executing its acquisition function.

4.2.2 Step 2

The base reconfigures its RF mode to a special-purpose, burst-TDD mode and begins transmitting data frames containing the synchronization and security codes (the remaining fields of the transmitted frame are written with the preamble sequence). The base's express purpose is to broadcast the synchronization code so that the handset will detect the base during the handset's next sniff cycle.

The burst-TDD mode is a sparse transmission mode in which the base's normal TX/RX TDD transmissions are interspersed with receive-only TDD frames. Specifically, a repeated "2-on/4-off" transmission scheme is used in which two normal TDD-frame transmissions are followed by four RX-only TDD transmissions. In this way, the base can transmit – albeit more sparsely – over a longer period on the acquisition channel before the transmission compliance period is exceeded. The base uses this means of transmission in an attempt to improve the chances of gaining the attention of the handset in cases of interference or weak signal strength (due to excessive range).

4.2.3 Step 3

At the expiration of the handset's sleep period the handset executes its sniff cycle. The handset enters a receive-only TDD mode for a small, fixed number of RF frame periods (e.g., 20). During this period the handset executes its acquisition function in an attempt to detect the base. As in Step 2 of section 4.1, the handset continually slips the time reference of its TDD period while analyzing the received data for the synchronization code from the base. Following each such slip, the handset remains at the current time reference for 3 TDD periods (15 ms). If the handset sees the base's synchronization code at any location in its 304-bit received frame and in any two consecutive TDD periods, the handset will declare the base found. If the code is not found at the current time reference, the handset slips its time reference and continues the search at the new reference point. If the base's code is not recognized within the fixed number of frame periods, the handset returns to its sleep cycle.

4.2.4 Step 4

Having detected the base, the handset programs its RF characteristic to a normal TDD mode and begins executing its acquisition function. The handset transmits its synchronization and security codes (the remaining fields of the transmitted frame are written with the preamble sequence). At this point the handset is performing the same operations as in Step 2 of handset-initiated acquisition.

4.2.5 Step 5

At this point the process mimics Step 3 of the handset-initiated acquisition process. The handset is transmitting and is slipping the time reference of its RF frame as it searches for the base's synchronization code. Eventually, the handset's transmit period will overlap the receive event of the base's burst-TDD RF frame. When the base sees the synchronization code at any location within its 304-bit RX frame in any 2 consecutive TDD periods, the base declares the handset found and transitions from the zero-interleaved TDD mode to the normal TDD mode. The base executes its traffic function and attempts to establish communications with the handset.

4.2.6 Step 6

As the base transitions from the burst-TDD mode to a normal TDD mode the handset is completes its acquisition function and snaps the time reference of its RF frame to that of the base. The handset executes its traffic function and attempts to establish communications with the base. The handset constructs a command to instruct the base to begin frequency hopping and pushes this command onto the handset's buffer of transmitted commands.

4.2.7 Step 7

The base establishes communications with the handset and enters its traffic mode.

4.2.8 Step 8

When the base and handset have established communications with one another the base sends a command to the handset instructing the handset to reset its frame-clock (25-frame counter). Having received the reset command from the base, the handset transmits the command to commence hopping until the base acknowledges receipt of the command. Frequency hopping will commence at the next frame-clock boundary, which is 25 frames after the base first acknowledges receipt of the handset's command to initiate hopping.

4.2.9 Comparison with the narrowband telephone platform

The FHSS platform differs from the narrowband platform in base-initiated acquisition in these aspects:

1) The FHSS platform initiates frequency hopping once communications have been established.
2) The FHSS base transmits in the burst-TDD mode (2-on/4-off) when attempting to get the attention of the handset. The narrowband platform transmits continuously in normal TDD mode.

3) Acquisition must be completed (communications established) before expiration of the transmission compliance period. The narrowband platform, being a low-power transmitter, can transmit continuously without restrictions on the duration of transmission within the acquisition channel.

4.3 Failed Acquisition Procedure and FCC Compliance Scheme

When communications are poor on the acquisition channel, due to interference or lack of sufficient signal strength, it is possible that the base receives the command to begin hopping at the next frame-clock boundary but the handset never receives an acknowledgment. In this case the base will start hopping while the handset will continue to transmit the hop command to the base in an attempt to get an acknowledgement. As soon as the base begins hopping the link will be destroyed. In such cases the base and handset both return to the sleep and sniff states after exceeding the transmission compliance period.

The base will transmit until either 1) the handset recognizes the base's transmissions, wakes-up, and establishes a valid link with the base or 2) the base exceeds the transmission compliance period on the acquisition channel (400ms total transmission duration). If the base fails to complete a link with the handset within the compliance period, the base will cease to transmit and return to the receive-only TDD mode.

5 RF Power Control

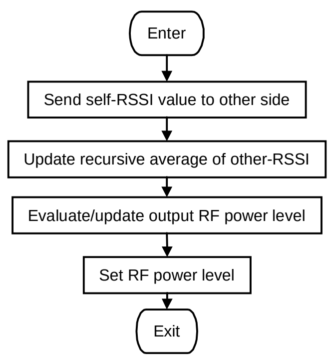

Figure 6. High-Level Flowchart of RF Power Control Algorithm.