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Suresh P. Singh

Power is a valuable resource. It is invaluable when for mobile devices. Mobile devices, due to their mobility cannot get a continuous source of power and derive their power from a battery contained in them. The main consumer of power in the mobile is its transmitter. With a limited power capacity of the batteries, it is always desirable that the transmit power of the mobile be minimized. The aim of this thesis is to introduce a new architecture to minimize this problem. It is called as "Stretchable Architectures". The stretched architecture involves an intermediary between the Mobile Station and the Base Station to carry the call between them. This type of connection is called a Stretched connection. We explain the energy efficiency of a Stretched Connection when compared to a Direct connection between the Mobile Station and Base Station. We investigate the factors affecting a Stretched connection and propose different Stretchable Architectures, suitable for different applications.

The "Stretched Architecture" is analyzed for the three 3G standards: Multi-carrier Direct Spread CDMA (CDMA2000), Wideband CDMA (WCDMA) and Time Division-CDMA (TD-CDMA).

STRETCHABLE ARCHITECTURES FOR 3rd GENERATION WIRELESS NETWORKS

BY

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STRETCHABLE ARCHITECTURES FOR 3rd GENERATION WIRELESS NETWORKS

1. INTRODUCTION TO CDMA

Code Division Multiple Access (CDMA) is a Multiple Access scheme, where multiple users can access the radio channel to communicate simultaneously. . CDMA is also called as Direct Sequence Spread Spectrum Multiple Access (DS-SS). The user's data is spread by a pseudo-random code sequence, and transmitted by a carrier frequency, which is also used by multiple users. The wireless communication channel between the Mobile and Base Station is prone to interference and propagation loss. Interference at the Mobile and Base Station receiver is dependent on interference from the same cell as well as interference from adjacent cells. Propagation loss is dependent on the distance between the Mobile and Base Station and type of terrain between them. As the propagation distance between the Mobile and the Base Station increases, the propagation loss increases non-linearly by a factor that depends on the terrain.

The link connection originating from the Mobile and terminating at the Base Station is called an Uplink or Reverse Link. The link connection originating at the Base Station and terminating at the Mobile is called a Downlink or Forward Link. The geographical area managed by a Base Station is called as a cell.

The link between the Mobile and Base Station is a single hop link, which can be called "Direct Link". The multiple access scheme used in this project to distinguish users is CDMA and we follow the 3rd Generation Wireless standards.

What distinguishes users or channels meant for the users are the unique and orthogonal pseudo random numbers used for spreading. At the receiver, the received signal can be despread only by the PN sequence with which it was spread and the original message can be extracted. Since signals from other users use different PN sequences which are orthogonal to each other, while de-spreading their signals appear as noise and when multiplied and integrated, should ideally become zero.

CDMA has many advantages over other multiple access schemes like Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA). Some of the prominent ones are:

a. Soft Capacity: The capacity of a CDMA system is called a soft capacity because there is no absolute limit on the number of users. This is mainly because CDMA systems take advantage of the idle period of a connection. For example, for speech, the voice activity factor is around 40%(LEE), which means that only 40% of the time is utilized for active speech communication while the remaining 60% is idle. Since a user is not using the channel always the interference level in the channel decreases, enabling more mobiles to be supported.

b. Multipath fading: The bandwidth of spread signal is much greater than the channel bandwidth. Correspondingly, the symbol period is smaller than the delay spread of the channel, which enables multiple versions of the signal due to multipath to be received at the receiver. The receiver at the Mobile and Base Station is a RAKE receiver that has multiple fingers, which correlate to the strongest multipath signals. The output of these fingers can be combined to enhance the received signal.

c. Soft handoff: No frequency planning is required in CDMA and adjacent cells can use the same frequency band. When a mobile moves from the old cell to a new cell, it needs to only use another PN sequence, but continue transmitting at the same carrier frequency. During soft handoff, the Base Stations in the old and new cell transmit the same information simultaneously. Taking advantage of multiple fingers in the RAKE receiver, few fingers correlate to multipath signals from the old cell and the remaining ones correlate to multipath signals from the new cell. This ensures that there is no discontinuation of communication between the Mobile and Base Station during handoff. This is Soft handoff.

But, CDMA has disadvantages also. Some of the prominent ones are:

a. Interference: CDMA is an interference limited multiple access system. As the number of users increase, the average interference increases, and when the average interference becomes greater than the thermal noise at the receiver, it begins to interfere with its signal. As previously stated, multiple mobiles in the same cell and mobiles from adjacent cells can use the same carrier frequency. Due to this, we have interference from mobiles in the same cell called as "Same Cell Interference" and interference from mobiles and Base Stations from adjacent cells called as "Other Cell Interference". It should be noted that interference is different for uplink and downlink channels because of the differing modulation and spreading schemes used for uplink and downlink [Lee]
b. Near-far problem: This problem occurs at the receiver of the Base Station. Signals from mobiles closer to the Base Station can overwhelm signals from mobiles far away from the Base Station without power control. In the uplink, the signals from the mobiles are not orthogonal and cause co-channel interference. This makes correlation at the receiver difficult. To avoid this problem, power control is adopted in uplink and this ensures signal strength from all the mobiles is same at the BS receiver.

2. THIRD GENERATION WIRELESS PROPOSALS

There are two proposals for the 3rd Generation Wireless networks. They are: cdma2000 and Universal Mobile Telecommunications System (UMTS). cdma2000 evolved from a current 2nd Generation wireless standard called IS-95, while UMTS evolved from another 2nd Generation wireless standard called Global Systems for Mobile Communications (GSM). Though there are many similarities between the two proposals, to provide backward compatibility with their predecessors, the two proposals do have some differences.

2.1. Duplexing Schemes

There are two duplexing mechanisms: Frequency Division Duplex (TDD) and Time Division Duplex (TDD). In FDD, uplink and downlink frequencies are different making simultaneous uplink and downlink transmissions possible, requiring no synchronization between uplink and downlink. FDD devices require diplexers, to separate the receiver from the transmitter.

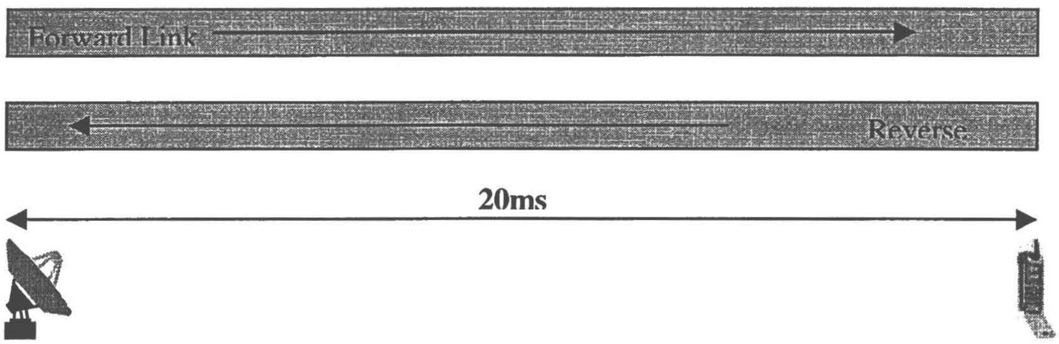


FIGURE 2.1: FDD Mode

In TDD mode, both uplink and downlink share the same frequency and their transmission is time multiplexed. This requires synchronization between uplink and downlink transmissions.

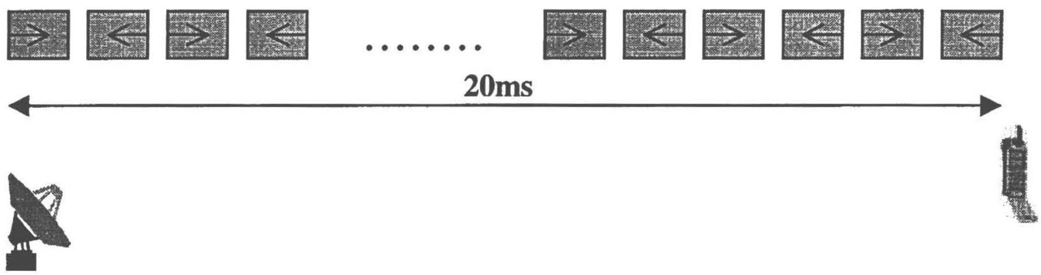


FIGURE 2.2: TDD Mode

2.2. CDMA Frame

A frame is the smallest unit of transmission. The frame duration in cdma2000 single carrier can be 5ms, 10 ms or 20ms, depending on the type of physical channel. A traffic channel frame is divided into 16 subslots called as Power Control Group (PCG), with duration of 1.25ms[CDMA2000-PHY]. A PCG contains 24 bits of data. The chip rate is 1.2288 Mcps per 1.25MHz carrier. The frame structure for a cdma2000 traffic channel is shown below.

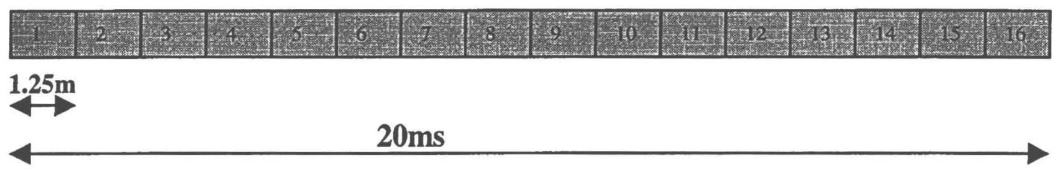


FIGURE 2.3: Frame in cdma2000

The UMTS' physical layer is called UTRA. UTRA has two modes: UTRA-FDD and UTRA-TDD. UTRA-FDD frame is either 5ms or 10ms long. An FDD frame consists of 15 PCGs with duration of 0.667ms[GARG], similar to the cdma2000 frame. UTRA-TDD comes in two modes: High Chip Rate TDD (TDD-HCR) and Low Chip Rate TDD (TDD-LCR). A TDD-HCR frame is either 5ms or 10ms long. It consists of 15 PCGs with duration of 0.667ms as shown in Figure 2.4.

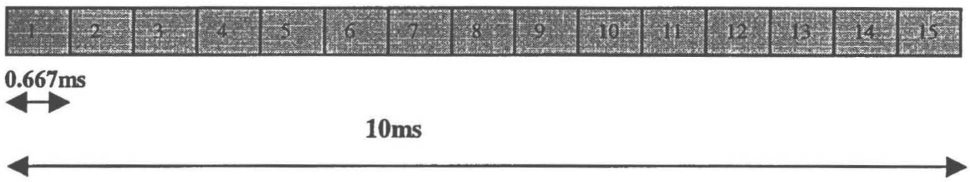


FIGURE 2.4: Frame in TDD HCR

The chip rate is 3.84Mcps and each slot structure is shown in Figure 2.5. The size of Data blocks varies. The guard band can have either 96 or 192 chips. The TPC is the power control bits that are punctured into the data segment.

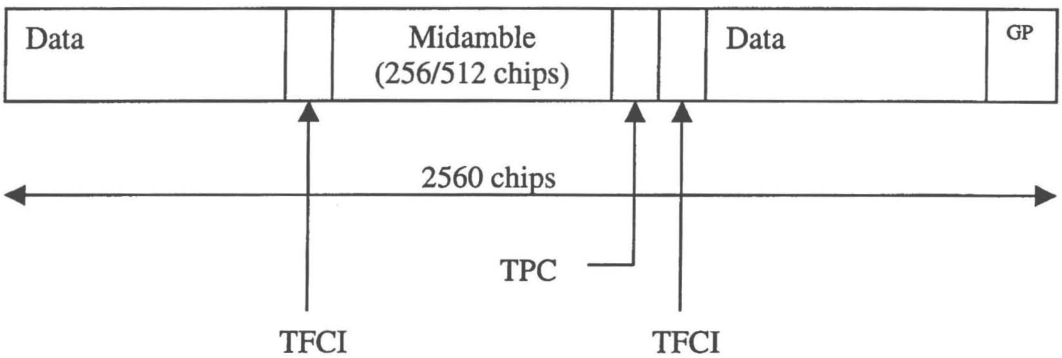


FIGURE 2.5: TDD HCR Frame Structure

TDD-LCR frame is 10ms long and divided into two subframes of 5ms as shown in Figure 2.6. Each subframe contains 7 time slots with the first time slot reserved for downlink and the second time slot reserved for uplink. A switching point separates uplink and downlink transmissions in the frame. A guard band prevents overlap of downlink and uplink transmissions, and downlink and uplink pilots ensure synchronization between uplink and downlink transmissions. Each slot structure is similar to that of TDD-HCR as shown in Figure 2.5.

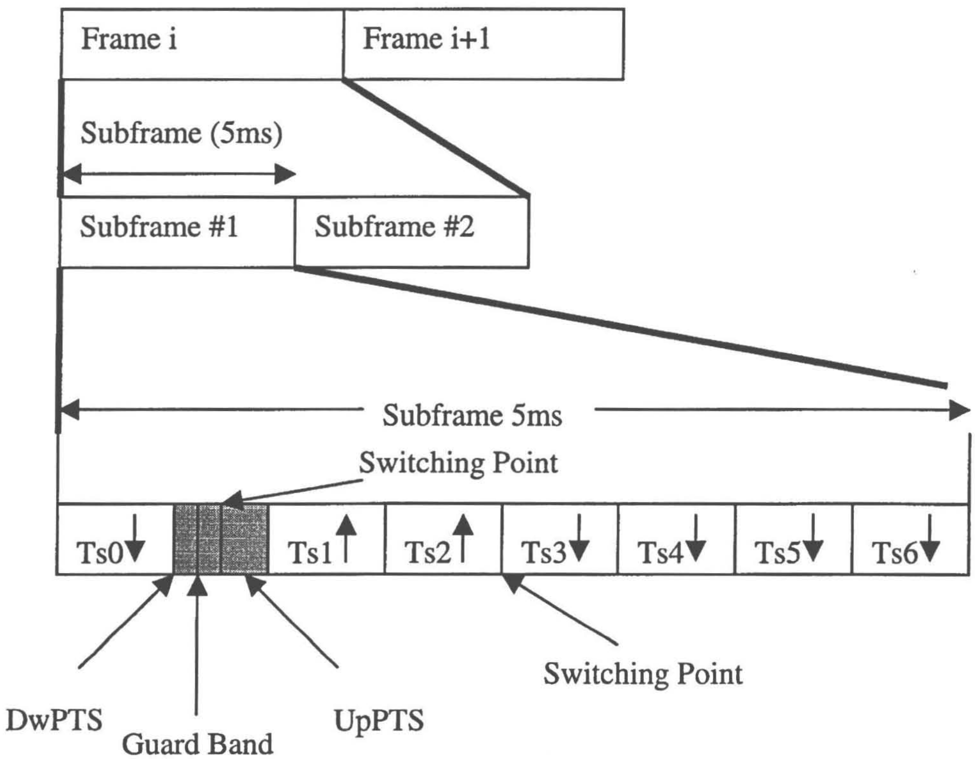


FIGURE 2.6: TDD LCR Frame Structure

While the high chip rate of 3.84Mcps in TDD-HCR provides high data rate, in TDD-LCR, advanced technologies like Smart antennas, uplink synchronization and joint detection provide similar data rates using a low chip rate of 1.28Mcps. TDD-LCR can be used for both symmetric and asymmetric traffic in pico, micro and macro cells. It can be used for both high and low mobility scenarios. TDD-HCR can be used for micro and pico cells for low mobility scenarios and is preferred for asymmetric traffic.

2.3. FDD Multi-carrier (cdma2000)

2.3.1. Forward Link

This section explains how the user's voice gets coded, modulated, spread before being transmitted by a 1.25MHz carrier. A vocoder converts voice to binary data. The output of the vocoder is 8.6kbps. To provide Error Detection, a Cyclic Redundancy Check (CRC) is performed on the vocoder output and the CRC appended to it. The resulting data rate is 9.2Kbps. Eight encoder tail bits are added, and this increases the data rate to 9.6kbps. This is then passed through a ½ rate convolution coder to provide Forward Error Correction. The output of the convolutional coder is a 19.2ksps. If the output of the vocoder is less than 8.6Kbps, then the output of the convolutional coder is less than 19.2 Ksps. But, the input to the Block Interleaver should be 19.2Ksps. Therefore, coded symbols are repeated for low data rates. This is valid for both voice and data. The Block Interleaver, provides protection from burst errors caused by fast fading. The interleaved bits are scrambled by a long PN code using user's unique phase offset. Scrambled bits are punctured at an average rate of 800 bps to insert power control bits. The power control bits are used to adjust the transmit power of the mobile, with the aim of keeping its signal strength at the BS receiver, the same as that of other mobile's signals.

The punctured bits are then spread by variable length Walsh codes to give a fixed chip rate of 1.2288 Mcps, increasing the data rate by a factor of 64-chips per scrambled symbol. There are 64 Walsh codes, which are orthogonal to each other and are used in the forward link to distinguish users. This orthogonally spread chip stream is passed to a QPSK modulator where it is again spread by a BS unique short PN offset before being transmitted by a carrier frequency.

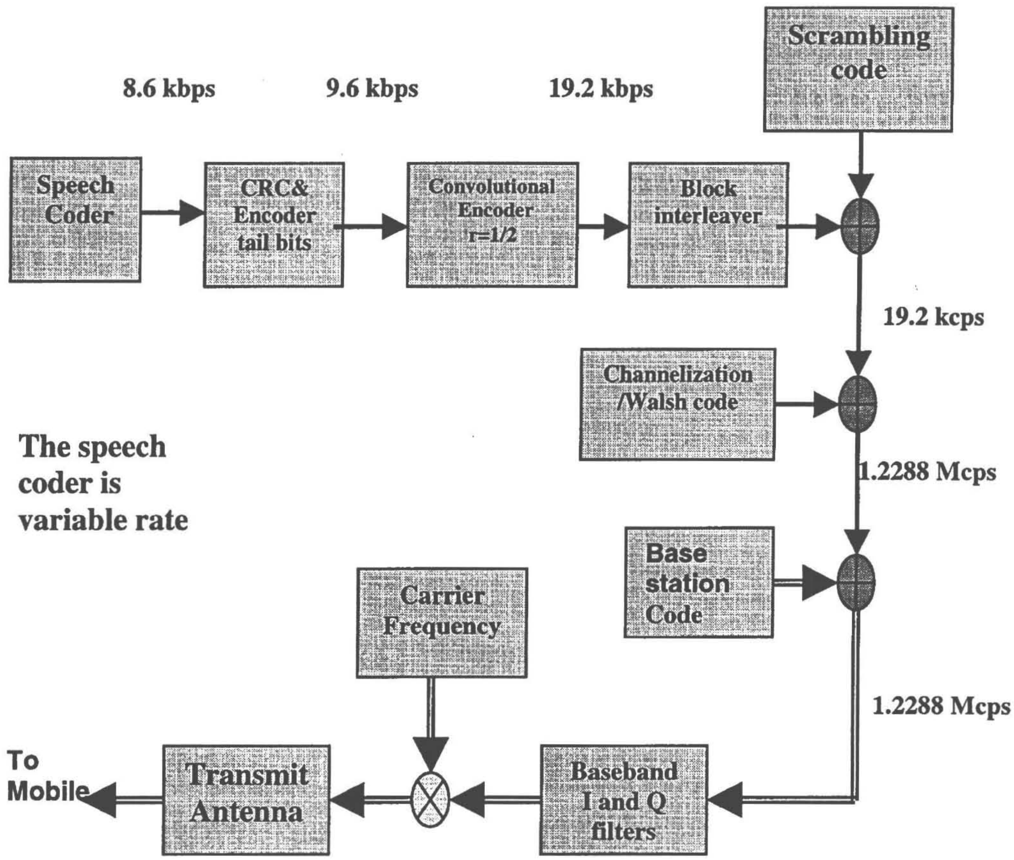


FIGURE 2.7: Forward Link

2.3.2. Reverse Link

Reverse link differs from the forward link in many aspects. The convolution coder is a 1/3-rate coder, giving an output of 28.8ksps. In case of low data rate, the coded symbols are repeated to make the input to the interleaver fixed at 28.8ksps. After interleaving, the symbols are modulated by variable length Walsh codes. 6 coded symbols are modulated into 64 Walsh chips. Therefore, if the input to Walsh modulator is 28.8 ksps, the output of the Walsh modulator = 28.8*64/6=307.2 kcps.

In the reverse link, to reduce the interference and thereby increase user capacity, repeated symbols from the repeater are gated off. Similarly, taking advantage of the voice activity factor, the data burst randomizer does not output any bits during periods of inactivity. This feature is used only in the reverse link. The output of the data burst randomizer is then spread by a long PN code, with a user specific phase offset. Before transmission, the chip sequence is spread by a BS specific short PN offset using Orthogonal QPSK, unlike QPSK in forward link before transmission. The reason for using OQPSK is to avoid zero transitions during modulation so as to maintain the mobile transmitter in saturation region, where highest power efficiency can be obtained [LEE]

It should be noted that there is only one long PN code and only two short PN codes. The short PN codes are unique to the network, offsets of which distinguish Base Stations.

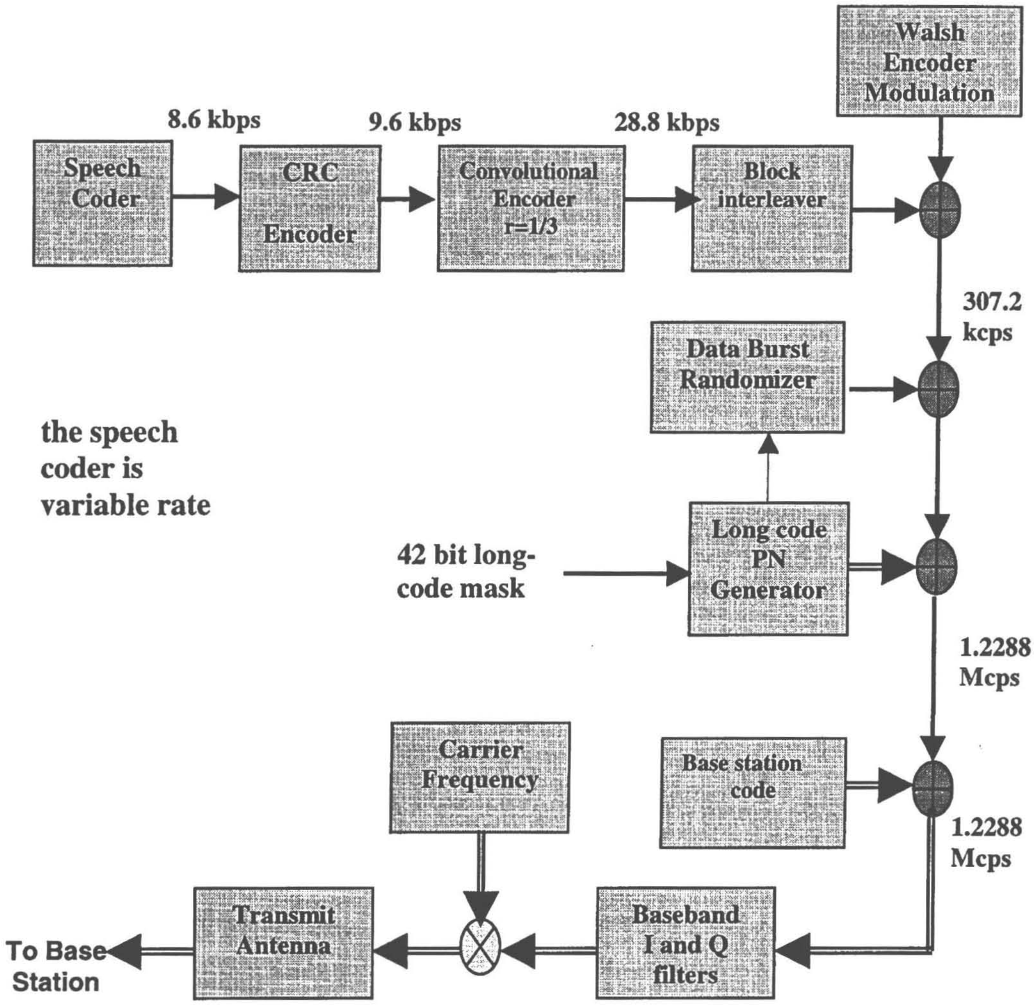


FIGURE 2.8: Reverse Link

2.4. FDD Direct Spread (UTRA-FDD)

In UMTS, the there are two dedicated physical channels that are transmitted simultaneously. They are Dedicated Physical Data Channel (DPDCH) and Dedicated Physical Control Channel (DPCCH). The DPDCH contains data generated by the upper layers, while DPCCH contains control information generated by Layer 1. The control information consists of pilot bits for coherent detection, Transmit Power Control (TPC) bits to control transmit power of the other end and an optional Transport Format Combination Indicator (TFCI) bits to provide information about mapping of logical channels to the physical channels in the current packet. In the Forward Link, the DPDCH and DPCCH are time multiplexed, while in the Reverse Link, they are code multiplexed.

2.4.1. Forward Link

After receiving a data block from the upper layers, CRC is appended to enable Error Detection at the receiving end. After adding the CRC bits, the data blocks are concatenated or segmented depending on their size, so that a fixed block size is always inputted to the coder. Channel coding provides Forward Error Correction and either 1/3 Convolutional coding or 1/3 Convolutional coding along with Reed-Solomon coding or Turbo codes are used. After coding, rate matching is done by puncturing bits in the coded block, so that it maps to the closest lower bit rate of the physical channel. If the code block size is small, then a Discontinuous Transmission (DTX) bit is inserted to inform the transmitter to stop transmitting.

The fixed size coded block is now fed to an interleaver to recover from burst errors at the receiver. This is the first of the two interleaving operations that is performed on the data and it is only done if a 10ms delay is permitted. If the transmission time is greater than 10ms, then the input sequence are segmented and mapped onto 10ms consecutive radio frames. A 10ms radio frame is the output from one transport channel. Different transport channels are multiplexed so as to achieve a continuous data stream in the physical layer. More than one physical channel can be used, depending on the number of transport channels. Physical channels are distinguished by their spreading codes. A final interleaving is done for every physical channel, before it is mapped on to one of the DPDCHs [FDD-MUX-CODING].

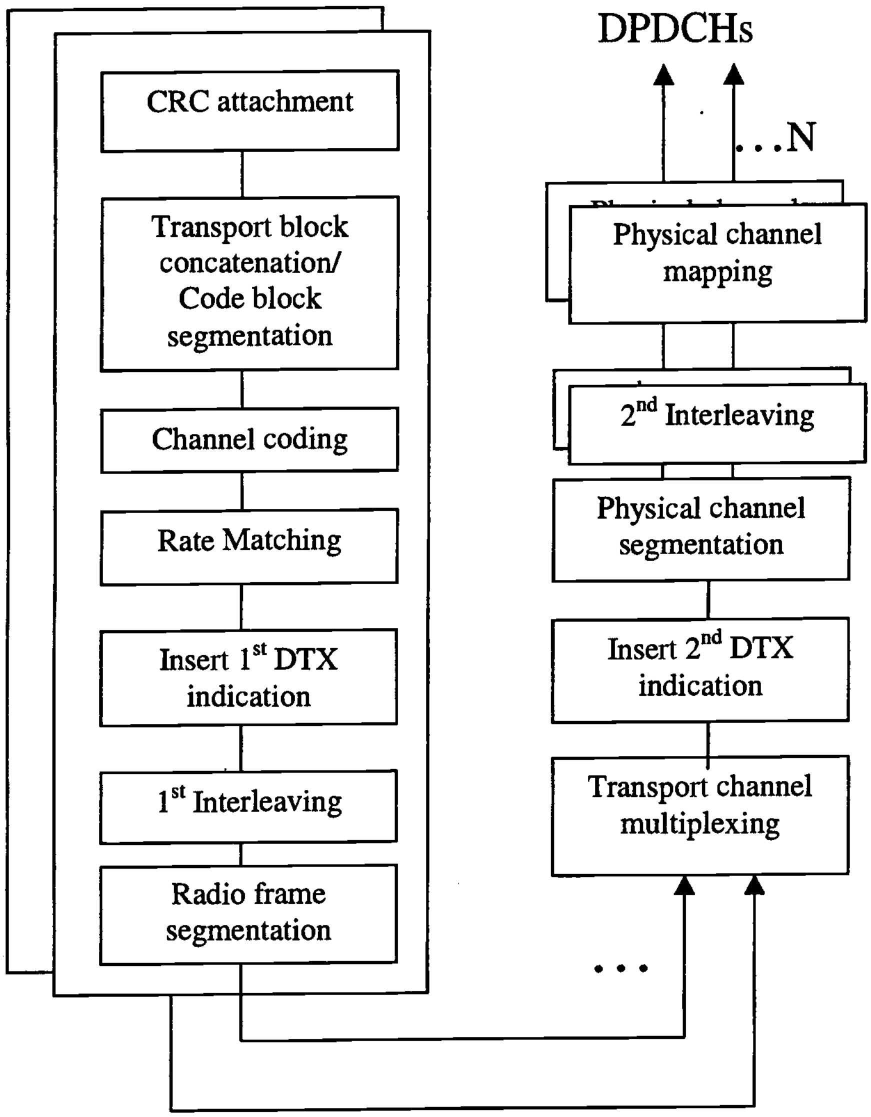


FIGURE 2.9: UTRA FDD Forward Link

Each DPDCH appends to a DPCCH and then fed into a Serial to Parallel converter, which splits consecutive pair of bits into I and Q branches. The I and Q branches are spread by a user specific Channelization code, scrambled by a cell specific scrambling code, QPSK modulated and then finally it is transmitted [GARG].

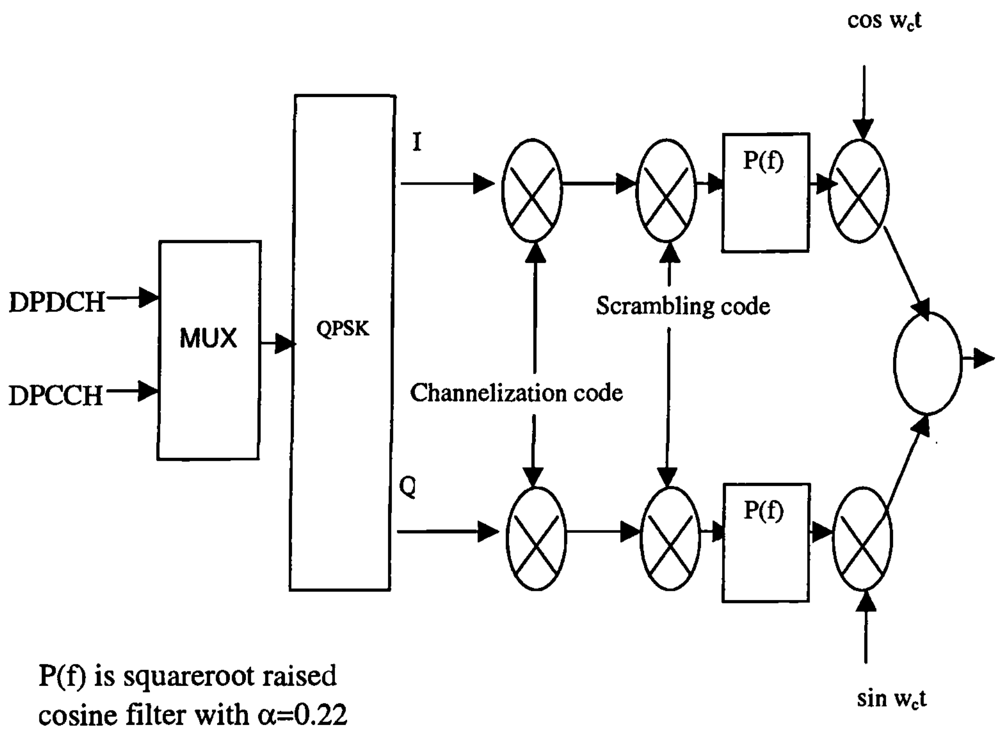


FIGURE 2.10: Forward Link Spreading and Modulation

2.4.2. Reverse Link

The reverse link is similar to the Forward link, with a few exceptions. There is a Radio Frame Equalization stage to divide the data into equal sized blocks, so that the input to the interleaver is a fixed sized block. Secondly, the order in which rate matching, interleaving and segmentation are done is different. Rate matching is done prior to interleaving so that transmission can be interrupted when the bit rate is low and the interleaver still gets a fixed sized coded block. Like the Forward link, if the number of bits does not fit into a radio frame, the coded block is punctured. But, if the number of bits in the coded block is less, then the data bits are repeated [FDD-MUX-CODING].

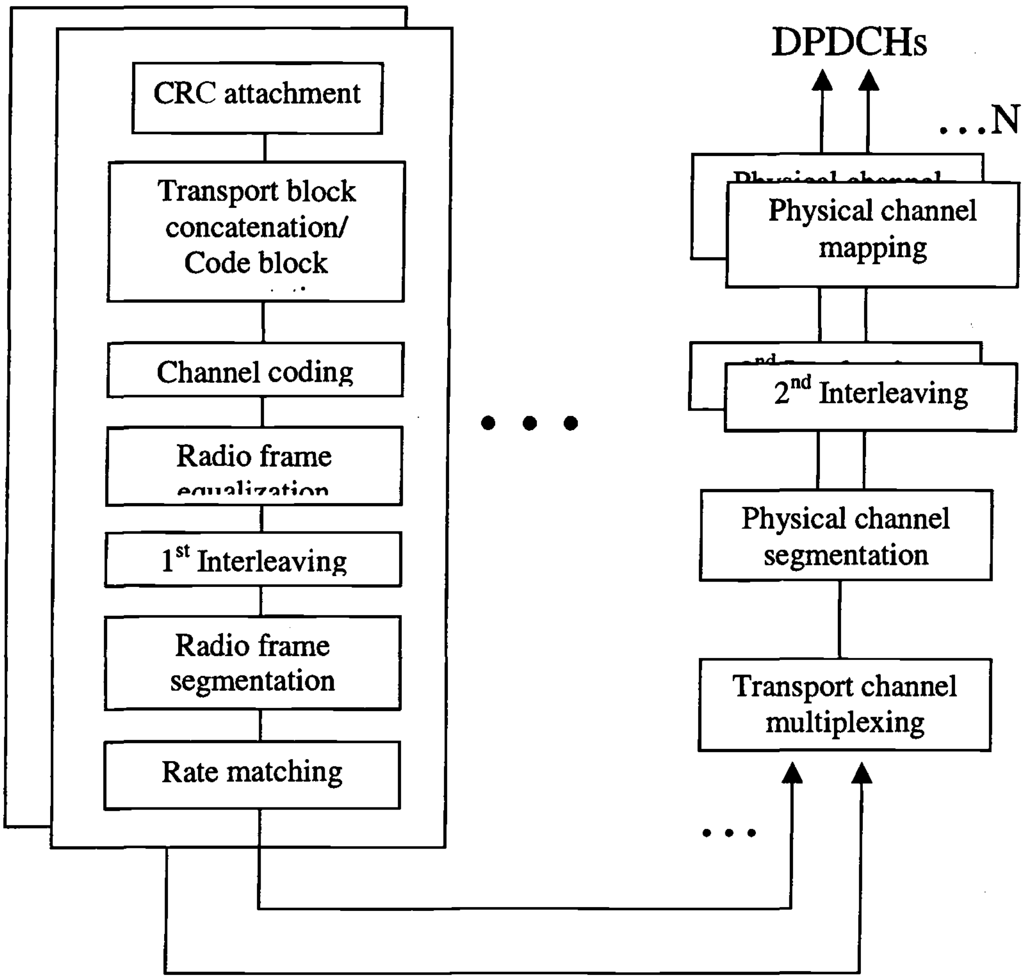


FIGURE 2.11: UTRA FDD Reverse Link

Each DPDCH is spread by a physical channel specific channelization code. Up to six DPDCHs can be combined with a single DPCCH per user, each with a different channelization code. The DPCCH is also spread with a unique channelization code. The scrambling code, which is unique to a user, differentiates users in the reverse link. These channels are complex combined and then scrambled by a mobile specific scrambling code, QPSK modulated and then finally it is transmitted [GARG]. It should be noted that the channelization and scrambling codes have different functionalities in uplink and downlink.

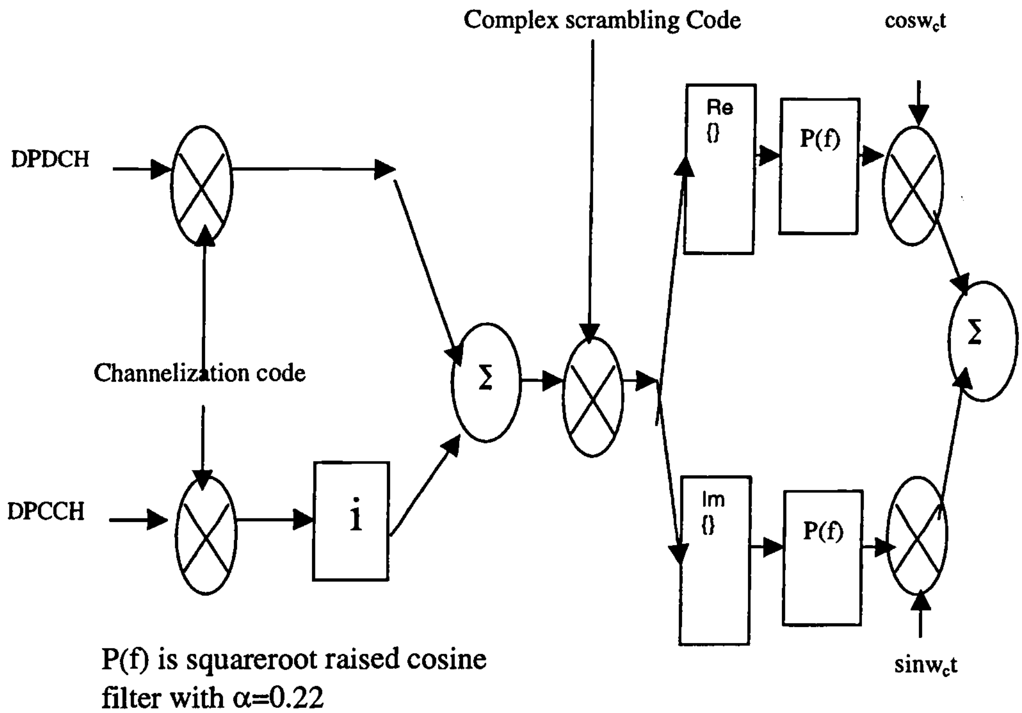


FIGURE 2.12: Reverse Link Spreading and Modulation

2.5. UTRA TDD-HCR

The physical layer multiplexing and coding for TDD-HCR uplink and downlink are similar to the FDD uplink specifications as shown in Figure 2.11, except for a Bit scrambling function that exists between transport channel multiplexing and physical channel segmentation [TDD-MUX_CODING]. Also, in TDD mode, the physical control channel information is not a separate channel and is embedded in the data channel. The structure of a TDD-HCR frame is given in Figure 2.5.

2.6. UTRA TDD-LCR

TDD-LCR is similar to TDD-HCR, but with one difference. The radio frame segmentation functionality provides segmentation of input data stream into 10ms blocks. But since the unit of TDD-LCR is a subframe, a subframe segmentation between the second bit interleaving and physical channel mapping function is required so that the physical channel transmits a 5ms block instead of a 10ms block [TDD-LCR-PHY]. The structure of a TDD-LCR frame is given in Figure 2.6.

2.7. Power Control

CDMA is an interference-limited system. Mobiles communicating with the Base Station in the same frequency cause the interference. Therefore, it is important to minimize the transmit power of the mobiles. Power control is more important in the Reverse link than in Forward link. While Forward link traffic channels are modulated by orthogonal Walsh codes, the reverse link traffic channels are modulated by a long PN code with a phase offset unique to a user. The phase shifted long PN codes are not orthogonal to each other and therefore, signals at the Base Station receiver interfere with each other. This causes two problems.

a. Near-Far problem. Signals from mobiles near the Base station can overwhelm the signals from mobiles far away by causing co-channel interference. Power control ensures that the received signal from all the mobiles near and far will be the same at the Base Station receiver.
b. Capacity reduction: If the mobiles transmit at minimal power levels to achieve the required SNR requirements at the Base Station receiver, capacity is maximized. If the transmit power of the mobiles increases, interference to other mobiles increases, thereby decreasing the capacity of the system.

3G systems use two power control mechanisms – Open Loop Power Control & Closed Loop Power Control.

2.7.1. Open Loop Power Control

In Open Loop Power Control, the signal strength of the received signal from the Base Station is used to determine the required transmit level for the Mobile. The assumption here is that forward and reverse channel properties are the same. Open Loop Power Control is employed during System Access phase, when the mobile is trying is initiate a call. Here, the mobile's RACH signal strength is dependent on the signal strength of the broadcast channels from the Base Station. The Base Station transmits the target E_b/N_0 and it's transmit power, so that the Mobile can calculate the Path Loss of the Base Station's transmission based on its received signal. Using this path loss and other interference information sent by the Base Station, it can calculate its transmission power. [LEE]

Open Loop Power Control is not suitable for FDD mode because the forward and reverse frequencies are different. But, this mechanism is most suited for TDD mode, where the forward and reverse links use the same frequency and therefore the propagation channel properties are reciprocal.

2.7.2. Closed Loop Power Control

In FDD mode, where the forward and reverse links are separated by 90Mhz, the forward and reverse link properties differ and therefore Open Loop Power Control is not accurate. Instead, Closed Loop Power Control is used, where the Base Station measures the received signal strength from the mobile's uplink transmission, and then sets the power control bits in the downlink traffic channel to notify the mobile to either increase or decrease the transmit power.

Closed Loop Power Control is achieved in two steps – outer loop and inner loop. The outer loop is used to set E_b/N_0 depending on the FER requirements. Since the channel properties dynamically change with Mobile's mobility and change in the propagation environment, E_b/N_0 may continuously vary and therefore, it has to be dynamically updated so as to maintain the required FER. Once the E_b/N_0 is set by the outer loop, in the inner loop, the mobile transmit power is adjusted using power control bits to match the E_b/N_0 requirements which in turn satisfy the FER requirements. FER can be verified using the CRC bits which are added before coding.

Closed loop power control is achieved with 800 power updates per second in cdma2000 and up to 1600 power updates per second in WCDMA. The power control bits can be punctured in every Power Control Group (1.25ms) in a frame. The Power control bits can be either a '1' or a '0'. A '1' indicates the mobile to decrease the transmit power and '0' indicates the mobile to increase the transmit power. The power can be increased in steps of 0.5dB to 2dB.

It should be noted that, when the Mobile is receiving duplicate signals from more than one Base Station during soft handoff and there is a contradiction in the power control update message, it will follow the power control update which informs it to decrease transmit power. This happens when one Base Station informs the Mobile to increase power, while the other Base Station informs the Mobile to decrease power. In this case, the Mobile will decrease power, assuming that it moving away from the former and approaching the latter Base Station. [GARG].

2.8. Handoff

As the Mobile moves around, it moves from one Base Station's coverage area into another Base Station coverage area. If during a handoff, the source and target Base Stations transmit simultaneously to the mobile during the handoff period, the handoff is called soft handoff. If the soft handoff takes place between two sectors of the same Base Station, then the handoff becomes "softer handoff". During soft and softer handoff, the operating frequencies of the source and target Base Stations are the same. If the source and target base Stations do not use the same frequency, then the handoff is called "hard handoff". The operating frequencies of the source and target Base Stations need not be the same. In FDD modes of CDMA, soft handoff is used predominantly because adjacent cells normally use the same frequency. Hard handoff is also supported in FDD mode, when the same frequency is not used. In TDD mode only hard handoff is supported and therefore, the Mobile can communicate with only one Base Station at a time. This is because of different synchronization requirements from the two Base Stations.

Soft Handoff is made possible in the hardware by the use of RAKE receivers, which correlate to the strongest multipath components and then combine at the demodulator to enhance the strength of the signal. Since cdma2000 and UMTS use wideband channels, the delay spread is much greater than the symbol period, and therefore, individual multipath components can be extracted.

2.9. CDMA Codes

There are different types of codes to enable "Code" Division Multiple Access. cdma2000 uses short and long PN sequence and Walsh codes. Short PN codes are used to separate Base Stations in both uplink and downlink. The Long PN codes are used to differentiate users in the uplink, while they are used to spread the signal in the downlink. The Walsh codes are used to modulate the signal in the uplink, while they are used to separate users in the downlink.

In UMTS uses Orthogonal Variable Spreading Factor (OVSF) and Gold codes are used. OVSF codes are used as Channelization codes and they separate multiple data and a single control channel in the uplink and users in the downlink. Gold codes are used as scrambling codes, and they separate users in the uplink and Base Stations in the downlink.

2.10. Security

From Sections 2.4, 2.5 and 2.6, we see that the physical layer processing is different for cdma2000 and UMTS. Different cryptographic algorithms have been proposed for cdma2000 and UMTS. In this sub-section, we briefly describe their security setup. In the security setup, Subscriber's Identity Module (SIM), Mobile

Equipment (ME), Base Station, Authentication Center, Home Location Register (HLR) and Visitor's Location Register (VLR) are involved.

2.10.1. UMTS Security Setup

The UMTS Authentication and Key Agreement (AKA) algorithm is called MILENAGE. It consists of seven functions, f1 – f7. MILENAGE uses Rijndael block cipher. Authentication is based on Challenge-Response mechanism. The mobile's SIM has a secret key, which is shared only by the SIM and the AuC in the infrastructure. When a connection has to be established, the AuC sends a random number, and a function using the secret key and the random number is executed. The result is sent to the Base Station, which verifies the result and authenticates the user.

For Ciphering and integrity f8 and f9 functions are used respectively. These functions implement a stream cipher derived from KASUMI block cipher in OFB mode. It should be noted that authentication extends from MS to the VLR, while encryption and integrity check extends from mobile to the BS. The ciphering algorithm to be used is determined based on the list of algorithms supported by the MS, which is sent to the BS. The BS selects the ciphering algorithm, but the integrity algorithm is negotiated. Integrity is provided for signaling information for establishing a valid connection.

UMTS ciphering/encryption is done either in MAC or RLC layer, depending on the RLC mode. In transparent RLC mode, acknowledgements are not required, while for non-transparent mode acknowledgements are required. For non-transparent RLC, ciphering is done in RLC layer, while for transparent RLC mode, ciphering is done in MAC layer. Speech and traffic use transparent mode and therefore encryption is done in MAC layer. Non-real time applications use non-transparent mode and encryption is done in LAC layer. [3G SEC_ARCH]

2.10.2. cdma2000 Security Setup

In cdma2000, Cellular Authentication and Verification Algorithm (CAVE) is used for AKA, encryption and integrity verification. The CAVE algorithm is also used for the generation of Shared Secret Data (SSD). SSD is stored in semi-permanent memory in MS, which is available for BS. It consists of 2 parts - SSD_A and SSD_B. SSD_A is used for authentication and SSD_B is used for voice privacy and message encryption. The Mobile and AuC share a primary secret: A-key. Other secret information is the manufacturer provided ESN and the network service provider given IMSI. Authentication is done again by a Challenge-Response mechanism, using the random number RAND, ESN and SSD_A by using the CAVE algorithm.

Key_VPM_Generation procedure is used for the generation of encryption and voice privacy mask. The encryption key - CMEA key is generated first and after eleven more iterations, the voice privacy mask is generated [MIT]. The voice privacy mask is also called as private long code mask. In cdma2000, voice privacy is provided in the physical layer using the private long code mask. In downlink, the private long code is used for scrambling, while for uplink, the mask is used to determine the phase offset of the long PN code, to spread the data. Signalling messages is encrypted using the CMEA key. CMEA is performed in the Link layer and therefore, the data to the encoder is already encrypted, unlike for voice, which is performed during spreading. For user data, probably IPSec is used.

The CMEA key is used to generate encryption keys for financial and non-financial data. This though is not mentioned in the cdma2000 specifications.

For user data - both financial and non-financial, the CMEA key is used to generate Enhanced CMEA keys for financial and non-financial data. Other than CMEA keys, the ORYX encryption system can be used for user data encryption. There is also the SCEMA encryption system used in IS-136, which can also be used. The usage of ECMEA and SCEMA is not specified in the cdma2000 specifications. If SCEMA encryption is used, which is done at the link layer, then voice confidentiality is provided in the upper.

3. TRANSMIT POWER CALCULATION

In this chapter, we first give an expression used to calculate the path loss and then obtain a relation used to calculate the transmit power as a function of path loss, Signal to Noise Ratio (SNR) and interference.

3.1. Path Loss Calculation

The general expression for received power is given by,

$$P_r = \frac{P_t G_t G_r \lambda^2}{d^2 (4\pi)^2} \tag{3.1}$$

where,

P_t is Transmit power

G_t is Transmitter antenna gain

G_r is Receiver antenna gain

λ is Wavelength

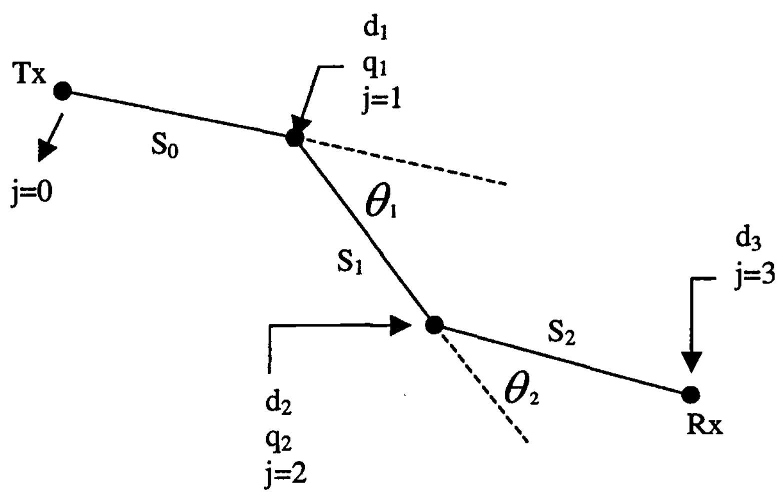
From the formula in equation (3.1), we see that the received power depends predominantly on the distance between transmitter and receiver. The value of path loss exponent is dependent on the propagation environment. For free space or Line of Sight propagation its value is equal to 2 and increases when obstructions are present. In an urban area, where the height of the mobile antenna is much lesser than the height of the buildings, its value varies between 2.7 to 6[RAPP].

In free space propagation, there is a break point, after which the path loss exponent increases from 2 to 4. The position of the break point is given by

$$d' = 12 h_t h_r / \lambda \quad \text{[LEE]} \tag{3.2}$$

Where,
h_t is Base Station Antenna height
h_r is Mobile Antenna height
λ is Wavelength.

In our experiments, we consider a microcell propagation environment for an urban area. From [UTRA][BERG], we can derive the path loss in an urban area using a recursive method. Consider the following street orientation in an urban area.



The distance d_n is an illusory distance defined by the recursive expression

$$d_j = k_j \cdot s_{j-1} + d_{j-1}$$

$$k_j = k_{j-1} + d_{j-1} \cdot q_{j-1} \tag{3.3}$$

with initial values,

$k_0 = 1$ and $d_0 = 0$ with

s_j is the segment length between two line of sight points.

The angle in radians between two segments is given by,

$$q_j(\theta_j) = \left(\theta_j \cdot \frac{q_{90}}{90}\right)^v \qquad (3.4)$$

$q_{90} = 0.5$

v = 1.5

The path loss using equations (3.5), (3.6) and (3.7) is given by

$$L_{dB}^{(n)} = 20\log\left[\frac{4\pi d_n}{\lambda} D\left(\sum_{j=1}^{n} s_{j-1}\right)\right] \qquad (3.5)$$

Where,

$$D(x) = \begin{cases} \dfrac{x}{x_{brk}}, x > x_{brk} \\ 1, x \leq x_{brk} \end{cases} \text{ and,}$$

x_{brk} = Breakpoint distance

The path loss calculated from (3.8) is used to calculate the transmit power required to satisfy the Signal to Noise Ratio (SNR) of the receiver.

3.2. Transmit Power Equation

We are interested in calculating the total energy expenditure of the Mobile and the intermediary when a Stretched call is used, and then compare with the energy spent by the Mobile, when it is making a Direct call. Depending on the Stretched Call Model (Section 5), the intermediary transmits to both Base Station and Mobile, or just to one of them. For TDD mode, the downlink spreading and modulation is similar to that of the uplink, while in FDD mode spreading and modulation differs in uplink and downlink.

3.3. Power Efficiency of Stretched Connection

A stretched connection is a two hop connection, where the connection between the Mobile and Intermediary is called the Lower Arm of stretched connection and the connection between the Intermediary and BS is called Upper Arm of stretched connection. Assuming the power distance relationship in Equation (3.1), the theoretical relationship between a direct and stretched connection is compared. This equation is for a free space propagation model, where the path loss component is equal to 2.

Let the distance between the Mobile and BS be 'd'. Let the distance between the Mobile and Intermediary be 'd_l' and that between Intermediary and BS be 'd_u'. Let P_{td} be the transmit power for the direct connection, P_{tl} be transmit power from mobile to the intermediary and P_{tu} be the transmit power from intermediary to the Base station.

Assume that the required power at the receiver is fixed at Pr. the transmit power required for a direct connection from Equation (3.1) is

$$P_{td} = \frac{P_r d^2 (4\pi)^2}{G_t G_r \lambda^2} \qquad (3.6)$$

For a stretched connection, the transmit power required by the Mobile to reach the intermediary is given by

$$P_{tl} = \frac{P_r d_l^2 (4\pi)^2}{G_t G_r \lambda^2} \qquad (3.7)$$

Transmit power required by the intermediary to reach the Base Station is given by

$$P_{tu} = \frac{P_r d_u^2 (4\pi)^2}{G_t G_r \lambda^2} \qquad (3.8)$$

The ratio of total transmit power required by Mobile for direct connection and the total transmit power required by Mobile and Intermediary combined is given by

$$\frac{P_t}{(P_{tl} + P_{tu})} = \frac{d^2}{(d_l^2 + d_u^2)} \qquad (3.9)$$

If d_l = $d_u = \frac{d}{2}$, then the ratio of direct and stretched connection powers is given by

$$\frac{P_t}{(P_{tl} + P_{tu})} = 2$$

Stretched connection is twice as power efficient as a Direct connection.

For a non-free space propagation environment, a log-distance Path Loss Model can be used to calculate the path loss. Its expression is given by the general expression from [RAPP]

$$PL(d) = PL(d_0) + 10n \log \frac{d}{d_0} \qquad (3.10)$$

where d0 is the reference distance which is determined by measurements close to the transmitter and d is the transmitter-receiver separation. The received power is given by

$$P_r(d) = P_t(d) - PL(d) \tag{3.11}$$

Equation (3.10) is equivalent to

$$PL(d)\alpha\left(\frac{d}{d_0}\right)^n \tag{3.12}$$

If the path loss component n = 3 and $d_l = d_u = \frac{d}{2}$, then the ratio of direct and stretched connection path losses is given by

$$\frac{PL_t}{(PL_{tl} + PL_{tu})} = 4$$

The Stretched connection is four times more power efficient than the Direct connection. Thus, we see that using a stretched connection is more power efficient than a Direct connection. [UTRA] shows the amount of power savings by using multiple hops.

4. STRETCHED CONNECTION

4.1. Introduction to a Stretched Connection

A Stretched connection has an intermediary, which can carry the call from mobile to base station and vice-versa. An intermediary can be stationary or mobile. A mobile phone with sufficient battery power, a car that always has enormous amount of battery power in its hood, can be intermediaries. Similarly, an immobile simple radio terminal, which is part of the network infrastructure, can also be an intermediary.

The intermediary can carry either the uplink or downlink or both. If the intermediary carries in only one of the directions, the stretched connection is called a Unidirectional stretched connection and if it carries in both the directions, it is a Bi-directional stretched connection.

If the intermediary is a TDD transceiver, then it can either transmit or receive at one time. Since the intermediary will have to transmit and receive to both Mobile and Base Station, it has to time multiplex four operations: transmission to BS, transmission to MS, reception from MS and reception from BS. This means that the intermediary is transmitting half the time and receiving half the time. This is the case for both symmetric and asymmetric traffic and it basically reduces the throughput of the system. Therefore, it is preferable to use the intermediary in FDD mode.

The intermediary might require a dual receiver, in case it has to receive from both Base Station and Mobile simultaneously. In bi-directional stretched connection, the intermediary has to time multiplex its transmission to Mobile and Base Station as we are assuming that the intermediary has only one transmitter. If the intermediary has more than one transmitter, then simultaneous transmission is possible to both Base Station and Mobile. But, in this case, a normal mobile cannot be an intermediary, but a sophisticated piece of hardware is required.

For the Base Station, the link to the intermediary is similar to a link to a Mobile. Higher layer signaling maps the Intermediary to the Mobile whose call it is carrying.

4.2. Factors affecting Stretched connection

4.2.1. Duplex mechanism

Based on the duplex mechanism used in the two arms of the Stretched connection, the possible combinations are:

a. TDD-TDD
b. FDD-FDD
c. TDD-FDD
d. FDD-TDD

In (a), (b) and (c), where TDD mode is used in both the arms or in one of the arms of the stretched connection, the intermediary is assumed to have an FDD like transceiver. As explained above, having a TDD transceiver at the intermediary reduces the connection throughput.

Within an FDD arm, the intermediary can receive and transmit simultaneously because the uplink and downlink frequencies are different. Within a TDD arm, the intermediary either transmits or receives at one time and therefore, a single frequency is used.

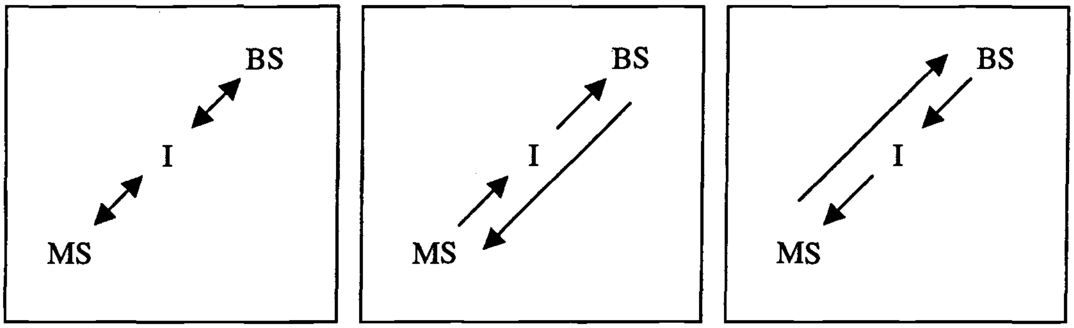
Closed loop power control is used for FDD arm to tone down the transmit power to minimal levels. As suggested earlier, open loop power control cannot be adopted for FDD mode because of different frequencies in uplink and downlink, which do not have reciprocal channel propagation properties. Though the same frequency is used in TDD transmission and reception, open loop power control is used only for the uplink. Closed loop power control is still used for downlink.

As we shall see in Section 5.3, each of these combinations is suitable for specific applications.

4.2.2. Direction

The intermediary can carry only uplink, only downlink or both. If the intermediary carries in only one direction, the stretched connection is called a Unidirectional stretched connection and it is a Bi-directional stretched connection, if it carries in both the directions. The different combinations possible are:

a. Bi-directional
b. Unidirectional Uplink
c. Unidirectional Downlink



Bi-directional | Unidirectional Downlink | Unidirectional Uplink

FIGURE 4.1: Bi-directional and Unidirectional Stretched Calls

4.2.3. Traffic Symmetry

a. Symmetric
b. Asymmetric

A symmetric Stretched Call is one, where the amount of traffic flow in both uplink and downlink is comparable – like in voice or interactive data applications. On the other hand, in an asymmetric stretched call, there is disparity in the amount of traffic in uplink and downlink. Some of the asymmetric applications are uploads, downloads, Internet browsing, etc.,

4.2.4. Propagation environment

The propagation environment between the upper and lower arms of the stretched connection can be similar or different.

The type of propagation environment in the two arms of the stretched connection make a difference in the number of time slots required for transmission for each arm. Propagation environments can be different for various reasons. Some of the possibilities are: lengths of the stretched connection arms are different, or one arm is in Line of Sight (LOS) and the other arm is in Non Line of Sight (NLOS).
The difference in propagation environment changes the information rate that can be supported in the two arms different and therefore, the number of transmission slots required in the intermediary differs for both arms of the stretched connection, even though the traffic is symmetric.

We know that the Signal to Noise Ratio (SNR) is given by,

$$SNR = \frac{E_b/N_0}{PG}$$

$$\text{where } PG = \frac{ChipRate}{InformationRate} \qquad (4.1)$$

As the propagation distance decreases, the SNR increases and therefore, to maintain a fixed E_b/N_0, the Processing Gain (PG) can be decreased from Equation 4.1. This means that a higher information rate can be supported. A decrease in the Processing Gain can be obtained either by increasing the coding rate or decreasing the spreading factor.

Coding rate (R) is given by

$$R = \frac{SymbolRate}{InformationRate}$$

where, Symbol Rate is the output of a coder and Information rate is the input to the coder.

In cdma2000 for example, for downlink a coding rate of ½ is used. By changing the coding rate to 2/3, more data symbols are coded at once. Keeping the spreading constant, and just changing the coding rate can support higher information rate. Spreading follows coding and the spreading factor is given by

$$SF = \frac{ChipRate}{SymbolRate}$$

where, Chip Rate is the output of spreading with a PN sequence and symbol rate is the input to the spreading process.

The Chip rate is fixed. In UTRA-FDD and TDD-HCR for example, the chip rate for a carrier is 3.84mcps. Therefore, by decreasing the spreading factor, the Symbol rate can be increased, which means, that for a fixed coding rate, the information rate is increased. In UTRA, the possible values that the spreading factor can take are given by $256/2^k$, where k = [0 .. 6]. Thus, the spreading factor can vary from 4 to 256 in factors of 2.

Thus, in our example, we achieved higher information rates either by increasing the coding factor or by decreasing the spreading factor.

The channelization codes used for spreading are Orthogonal Variable Spreading Factor (OVSF) codes. From [UTRA] a physical channel is assigned a spreading factor, so that all the users using the physical channel should use the same spreading factor. They cannot use any other spreading code in the OVSF tree. Therefore, it is not possible to retain orthogonality by dynamically changing the spreading factor. The only alternative then, is to vary the coding.

If the two arms of the stretched connection are of comparable lengths, then the same spreading factor has to be used for both of them. By varying the spreading factor, low and medium data rates can be supported. For high rate data transmission, spreading is coupled with multi-code transmissions.

4.2.5. Security

The security setup in cdma2000 and UMTS are different. In cdma2000, voice privacy is provided at the physical layer after interleaving. Since voice security is provided by private long code mask, advertising this mask to the intermediaries enables the intermediary to read the digitized voice, which is a big restraint. For data and signaling messages, encryption is performed at the link layer.

In UMTS, voice and data encryption are provided at the Link layer and the physical layer does not participate in security mechanisms.

4.2.6. Power Control & Forwarding

Depending on the choice of either closed loop or open loop power control mechanism, the forwarding mechanism at the intermediary changes. We know that there are two power control mechanisms.

a. Closed Loop Power Control
b. Open Loop Power Control

The choice of power control irrespective of whether TDD or FDD is used has a significant effect on the choice of the Stretched model. As discussed earlier in Section 2.8.2, closed loop power control requires calculation of FER from the CRC bits introduced before coding and modulation. If the intermediary is required to implement closed loop power control, then the intermediary should also be able to demodulate, decode and then verify the CRC bits. For this, the intermediary should gather a frame length of data (5ms, 10ms, 20ms etc.,) before it can verify the CRC. This means that the intermediary cannot immediately forward a PCG (1.25ms) it receives in the next slot (cut through routing). It should save a frame, verify the FER and only then forward it to the other side. Instead, a save and forward routing mechanism has to be followed by the intermediary if closed loop power control has to be used.

If Open loop power control is used, then power control is based entirely upon E_b/N_0 and therefore a simple cut through routing mechanism can be used in the intermediary.

For traffic channel, closed loop power control is used in FDD modes and in TDD downlink. Open loop power control is preferred only in TDD uplink. If closed loop power control it adopted, it introduces delay in the intermediary. So accordingly, in our proposal, the unit of transmission is a frame and we use the Store and Forward technique at the intermediary. This is also logical because if the intermediary used cur through routing, the Base Station receiving the signal cannot find out if the error in the frame happened in the upper arm or the lower arm.

4.2.7. Handoff

FDD mode use soft handoff, while TDD mode uses hard handoff. Therefore, in FDD mode, more than one BS can be involved in the communication with the MS during handoff and the connection continuity is maintained. On the other hand, in TDD mode, only a single BS is involved even during handoff, and therefore the Mobile should switch to the target (new) Base Station by stopping communication with the source (old) BS. This is caused because, both BS' have different synchronization requirements and therefore simultaneous reception and transmission with both the BS is impossible. Also, in TDD mode, the Resource Unit (RU) assignment, which is a combination of frequency and time slot, can differ with both Base Stations.

But in our case, it is assumed that the Mobile is assigned a RU unique in the cell. All intermediaries communicating with the Mobile will use that RU. Therefore, handoff between intermediaries can be soft handoff similar to as in FDD mode.
Due to the difference in distances between the mobile and intermediaries and their mobility, the delay spread continually changes and therefore the search windows have to be dynamically updated so that the Mobile can track signals from multiple intermediaries.

4.2.8. Delay

The intermediary receives the signal from one arm, demodulates, de-spreads, de-scrambles it in case of downlink, de-interleaves and decodes the data. It calculates the FER, which is useful to decide the value of the power control bit. Also, for Non-real time data, the Radio Link Protocol (RLP) in Link layer uses this information for controlling retransmissions.

For transmission, it recalculates the FER, codes, interleaves, scrambles, spreads and modulates before transmitting to the other arm. So, we see here that delay is introduced because the whole frame has to be received before FER can be calculated. So, using an intermediary introduces delay of twice the frame length duration. So if a 20ms frame is used as in cdma2000, then around 40ms of processing delay is introduced at the intermediary. Using shorter frames like 5ms as in TDD-LCR can reduce the delay much further.

[UMTS-QOS] specifies that one-way delay from UE to the PLMN is100ms. The tolerable delay for voice for example is 150ms – 400ms for one way. So, adding an extra 10ms – 40ms delay due to the intermediary should be tolerable.

5. STRETCHED CALL MODELS

In this section, we describe some of the possible stretched call models. The models are divided into two broad categories: Bi-directional and Unidirectional. For each of the categories, symmetric and asymmetric traffic scenarios are considered. Finally, the effect of unequal lengths of the upper and lower arms is investigated.

Each figure is divided into three parts. The top most part denotes the Base Station transmitter and receiver. The middle part denotes the Intermediary's transmitter and receiver and the bottom part denotes the Mobile's transmitter and receiver. The unit of transmission is a frame and in our figures, it is 10ms, as in UMTS. To differentiate between received and transmitting frames, the received frames are represented by dotted blocks. PC refers to Power Control information, which has to be sent to control the transmitter's power.

5.1. Bi-directional Models

For bi-directional stretched connection, both arms of the Stretched connection can use the same duplex mode or can use different ones. Thus, all the four duplexing mechanisms listed in Section 4.1.1 are possible.

5.1.1. FDD-FDD Model

5.1.1.1. Symmetric Models

Both arms of the stretched connection use FDD and closed loop power control is adopted in both arms of the Stretched call. For closed loop power control, power control bits can be sent every Power Control Group (PCG). The intermediary time multiplexes between upper arm and lower arm. Both uplink and downlink occur simultaneously so that power control bits can be sent immediately to instantaneously control the transmit power. The smallest unit of transmission is a frame to enable calculation and verification of FER.

Some of the possible FDD-FDD stretched models are shown in Figures 5.1, 5.2 and 5.3. In Figure 5.1, the intermediary multiplexes between upper and lower arms for each frame. This is the basic model. Figure 5.2 shows another possible model, though the delay here is much higher. The only advantage with this model is that power control can be more efficient as there is sufficient time to adjust the transmit power, unlike in Figure 5.1.

It should be noted that the specifications say that Discontinuous Transmission (DTX) is permitted only in the downlink. Therefore, without any physical layer modifications, model shown in Figure 5.3 seems to be ideal. But, the intermediary compresses data from two frames. The compression can be done either by using lower spreading factor or by increasing the coding rate. Since lowering the spreading factor decreases the number of available OVSF or Walsh codes, increasing the coding rate seems to be a better choice. Also, the power control is slow, unlike in Figure 5.1 and Figure 5.2 because there is no continuous transmission and reception.

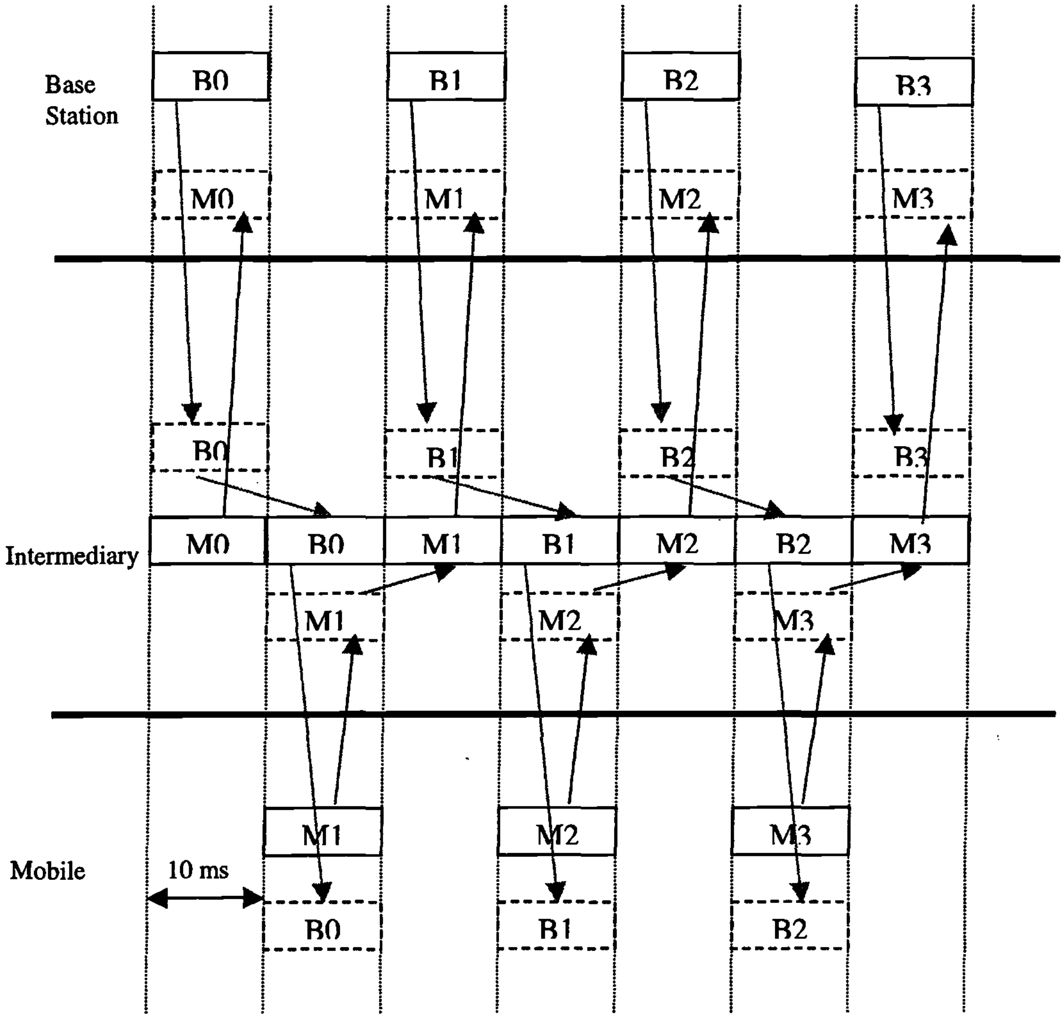


FIGURE 5.1: FDD-FDD Symmetric Model

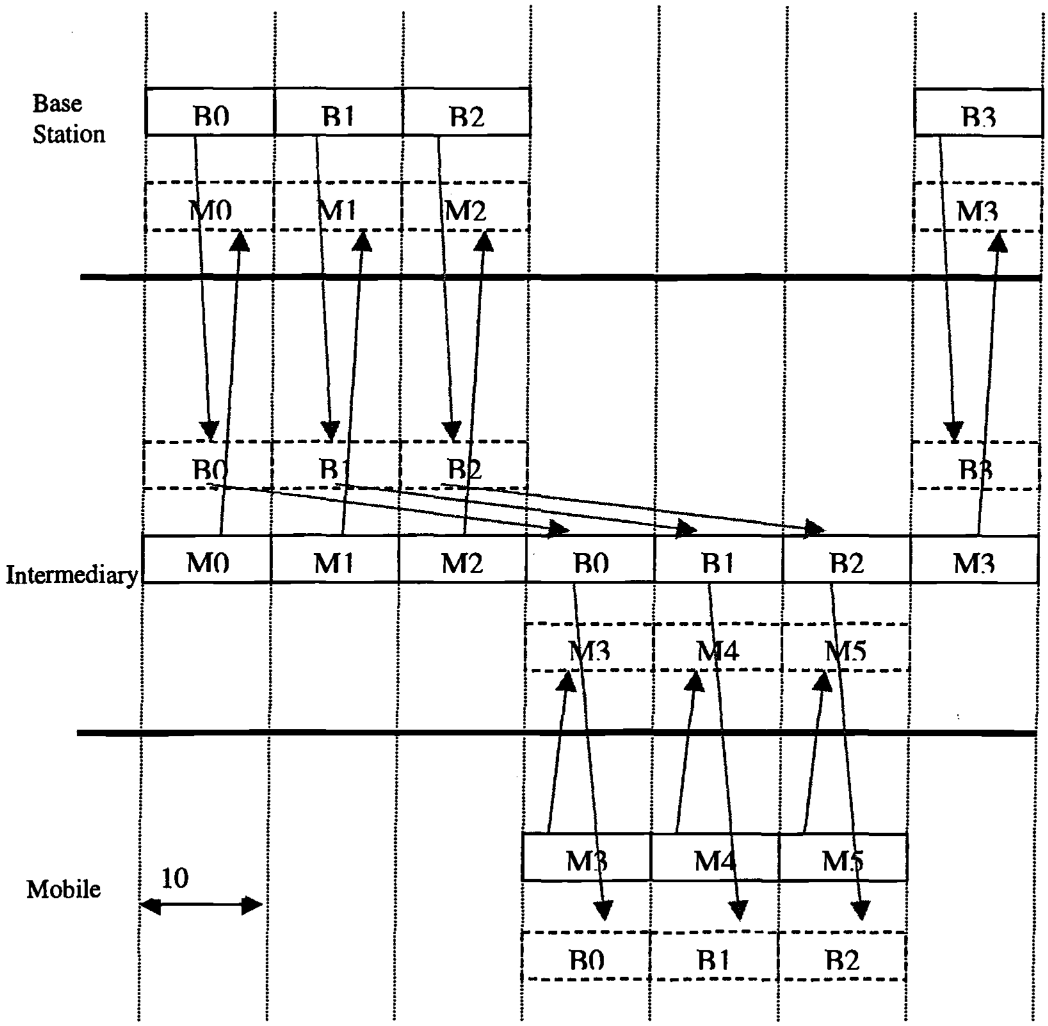


FIGURE 5.2: FDD-FDD Symmetric Model

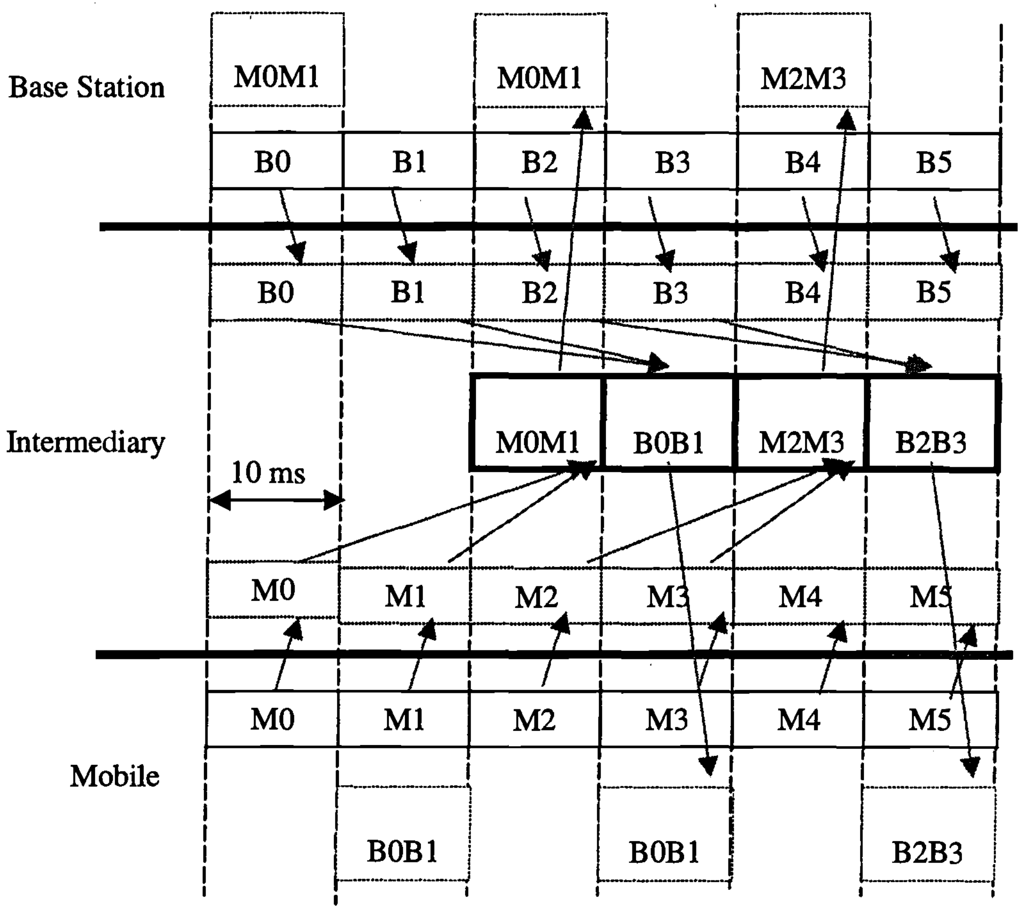


FIGURE 5.3: FDD-FDD Symmetric Model

Applications:

UTRA-FDD: For voice and Data. Encryption is provided in MAC and/or LAC layer and therefore security is not a problem.

cdma2000: Only for data. This is because, voice encryption is provided after interleaving, and this requires the intermediary to know the private long PN offset.

Disadvantages: There is a delay of twice the frame length introduced in the intermediary for the purpose of closed loop power control. Also, the bandwidth is not efficiently utilized, because of discontinuity in transmission. The bottleneck is in the intermediary, which cannot transmit simultaneously to both BS and MS.

5.1.1.2. Asymmetric Model

This model is similar to the Symmetric model. The reason is that closed loop power control is required when operating in FDD mode. This means that even though the traffic is predominantly in one direction, power control information has to be sent in the other direction to control the transmit power of the source. Therefore, though there is no flow of data, there is flow of control information and due to this we effectively have a symmetric model similar to the Symmetric FDD-FDD model.

If the power control updates can be decreased, then the model becomes more and more asymmetric, which is applicable only when the fading environment between the mobile, intermediary and base station does not change. In the figure 5.4, shown below, the red lines indicate control channels, which contain power control bits.

Advantages: Single receiver and single frequency is sufficient, as the intermediary is not receiving from both arms of the stretched connection at the same time.

Disadvantages: Since the intermediary spends half the time sending control channel for power control bits instead of data, the intermediary is not efficiently utilized and therefore, there is wastage of spectrum and the throughput is low.

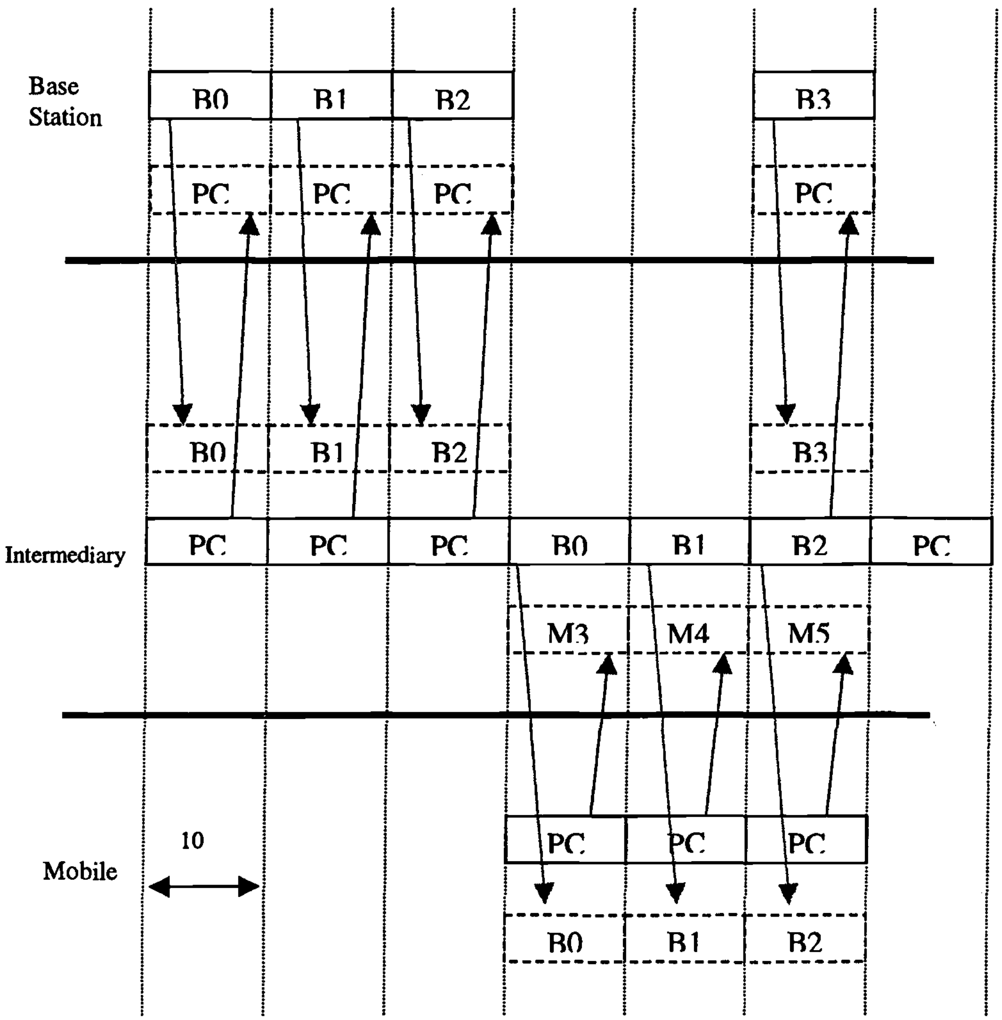


FIGURE 5.4: FDD-FDD Asymmetric Model

5.1.2. TDD-TDD Models

In these models, both arms of the stretched connection use TDD mechanism. The specifications say that downlink should use closed loop power control, while the uplink should use open loop power control. In the uplink, TPC bits are set, so that the BS can control it's transmit power. The Mobile will calculate the received power and from the TFCI bits sent in the downlink, will know the transmit power. From this, it will calculate it's transmitting power. Since the uplink and downlink use the same frequency, the channel propagation properties are reciprocal. [HAARDT]

Both upper and lower arms use different frequencies, so that the intermediary can receive simultaneously from BS and Mobile. Also, it is possible for the intermediary to receive from one arm and transmit simultaneously to the other arm.

Since in each arm, TDD mode is used, transmission and reception is multiplexed. Therefore, a single Walsh/OVSF code can be used. Since the upper and lower arms use different frequencies, the same code can be used in both arms of the stretched connection for both uplink and downlink.

5.1.2.1. Symmetric Model

A possible symmetric model, using intermediary is shown in Figure 5.5. It differs from the FDD models in that the Mobile either receives or transmits at any point of time. Since traffic flows symmetrically in both directions, power control information is sent along with the data.

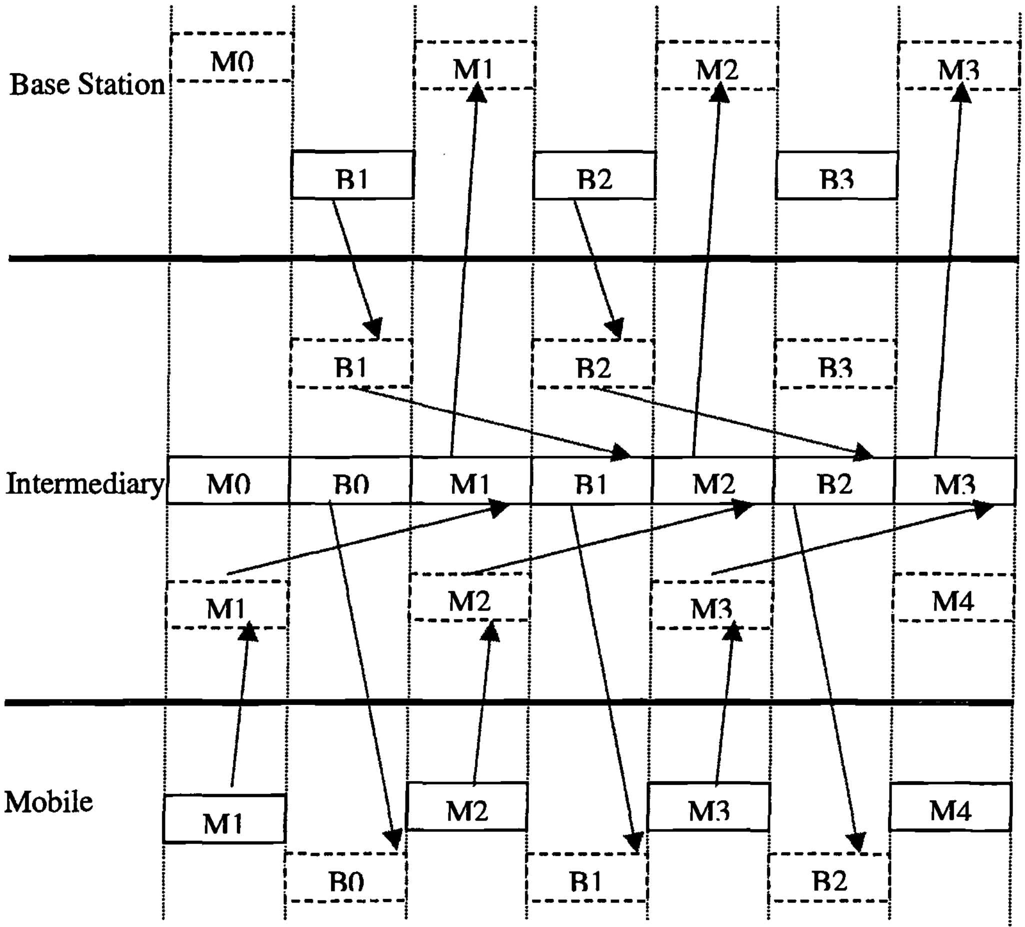


FIGURE 5.5: TDD-TDD Symmetric Model

Applications:

UTRA-TDD: Voice and symmetric data in low mobility scenarios.

cdma2000: Not supported, as TDD mode is not specified.

5.1.2.2. Asymmetric Model

A possible Asymmetric TDD-TDD model is shown in Figure 5.6. This model is similar to the FDD-FDD asymmetric model because closed loop power control is used in the downlink. TDD frame must contain at least one downlink slot in both TDD-HCR and TDD-LCR. Therefore, if the traffic is predominantly uplink and the channel properties do not change rapidly, the power information it obtains from the single downlink slot can be used to determine transmitting power in the uplink.

For a predominantly downlink on the other hand, it is the same as Asymmetric FDD-FDD model in Figure 5.4, as the mobile and intermediary should send power control information to intermediary and Base Station respectively in the uplink to maintain a closed loop power control.

Applications:
UTRA-TDD: This model is suitable for both TDD-LCR and TDD-HCR. It is preferred for predominantly uplink traffic in slow mobility scenarios.
cdma2000: Not supported.

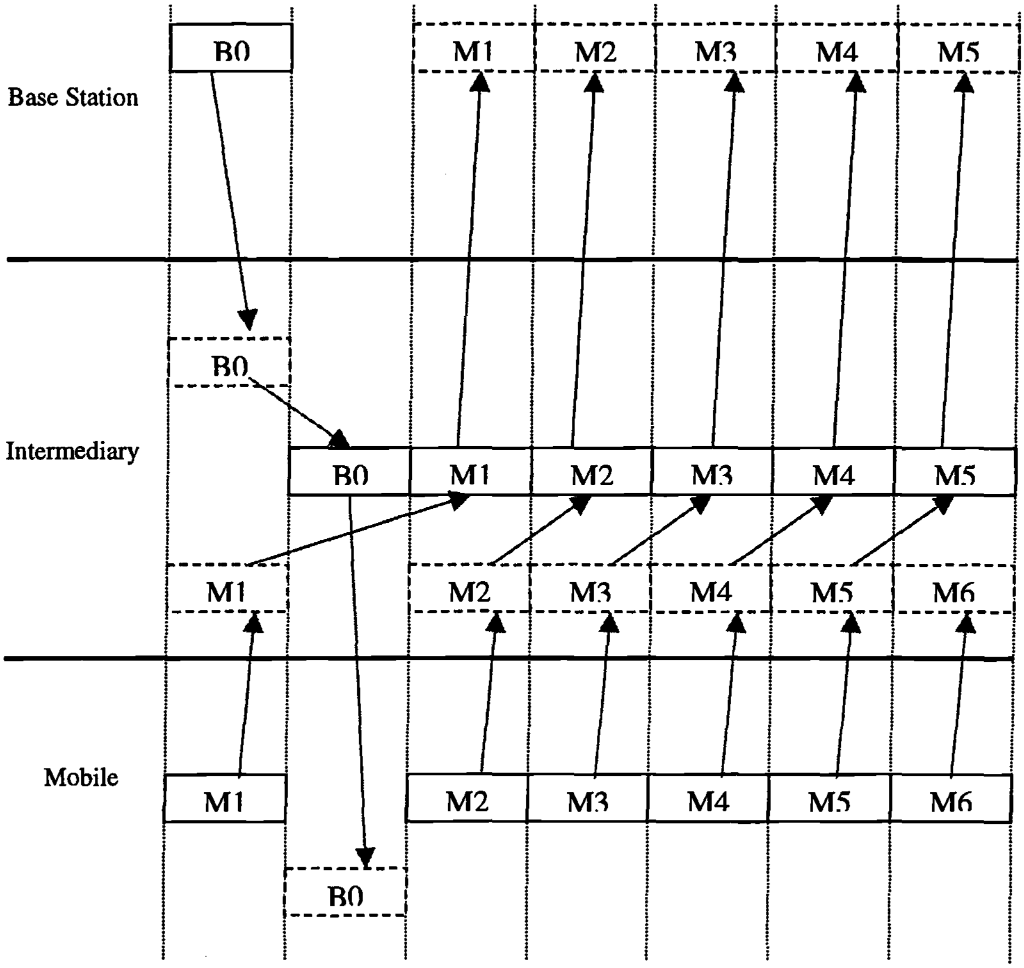


FIGURE 5.6: Asymmetric TDD-TDD Model

5.1.3. FDD-TDD

In this model FDD is used in upper arm and TDD in lower arm. The FDD and TDD operating frequencies are different and therefore the upper and lower arms use different frequencies. Like in other models, the same OVSF/Walsh code can be used for both uplink and downlink in both arms of the Stretched connection.

Since closed loop power is required in the upper arm for FDD mode, the unit of transmission is a frame, as the intermediary will have to calculate FER for uplink and verify FER for downlink of the upper arm. It should be noted that the frame structure for the lower arm is different from the upper arm in view of different modes of operation.

The intermediary has a dual receiver, with one receiver tuned to the downlink frequency of base station and the other tuned to the TDD frequency of the lower arm. The transmitter time multiplexes between upper and lower arms and uses the uplink frequency to base station in upper arm and the TDD frequency for the lower arm. The upper arm uses closed loop power control, while the downlink of lower arm uses closed loop and uplink of lower arm uses open loop power control, as required [TDD-SIM].

5.1.3.1. Symmetric Model

A possible FDD-TDD Symmetric model is shown in Figure 5.7. As we can see, this model is similar to TDD-TDD symmetric model because the Mobile can either transmit or receive at one time and this affects the upper arm also. The only difference is that simultaneous uplink and downlink transmissions are possible in the upper arm. Though the figure shows the unit of transmission is a frame in the lower arm, atleast one slot is assigned to the uplink and downlink in every frame. The disadvantage with this model is that the upper arm is idle half the time and therefore, higher throughput cannot be achieved.

Applications:

UTRA: Voice and Symmetric data.

cdma2000: Not applicable.

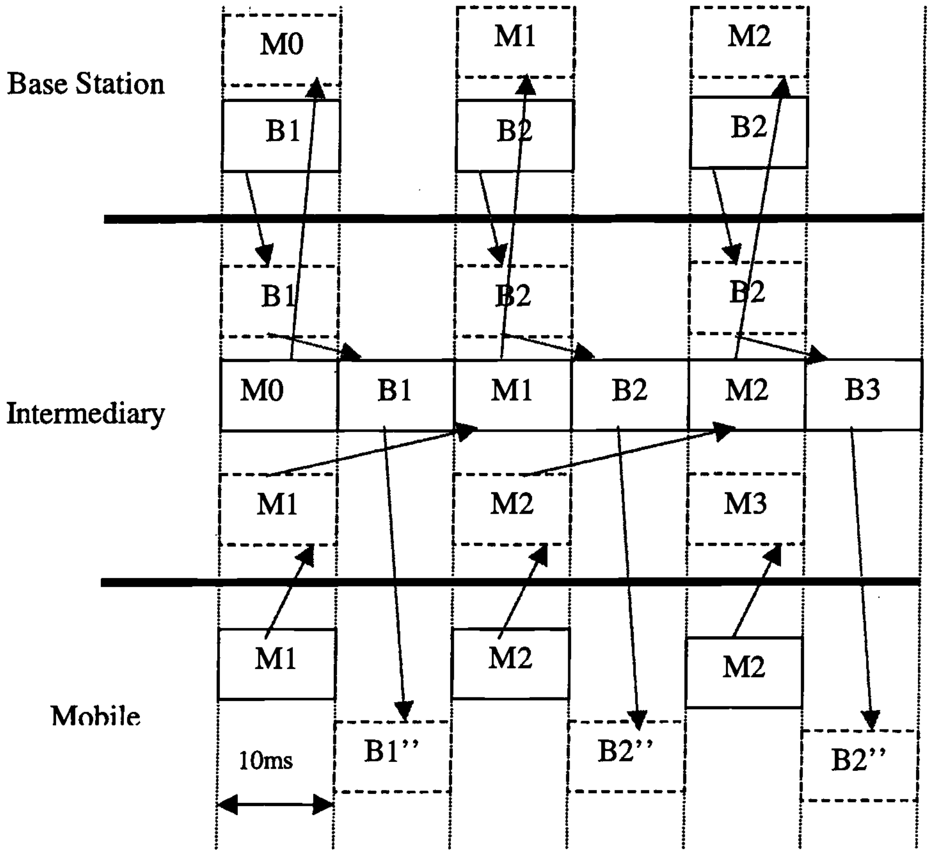


FIGURE 5.7: FDD-TDD Symmetric Model

5.1.3.2. Asymmetric Model

The figure 5.8 shows a possible FDD-TDD Asymmetric model. In this model, the traffic is predominantly uplink. In the upper arm, the intermediary is sending data along with the power control bits. Therefore, the intermediary does not have to explicitly send power control information. Therefore this model is more efficient for a predominantly uplink transmission when compared to a predominantly downlink transmission.

In the lower arm, the downlink uses open loop power control and the mobile does not need power control updates to be sent at a faster rate like in FDD mode. Therefore, when compared to the FDD-FDD asymmetric model, the intermediary spends more time transmitting data to the BS, rather than spending time in transmitting power control information to the Mobile. But since at least one slot in a TDD frame has to be used for the downlink, the intermediary should use discontinuous transmission (DTX) in the upper arm, so that it can send at least one frame to the lower arm.

Advantages: In a low mobility or stationary environment, 15 slots can be used for uplink and one slot for downlink and there by supporting higher data rates. This model gives the highest possible uplink data rate because the intermediary has to only transmit data and not power control updates. Every other model has to transmit power control updates. Though the upper arm is FDD, the power updates to the base station are sent along with the data it forwards from the mobile.

Disadvantages: If the lower arm's propagation environment changes rapidly, this model reduces to the symmetric FDD-TDD bi-directional model, because of the need to transmit power control updates in the lower arm.

Applications:
UTRA: Uploads
cdma2000: Not applicable as TDD mode is not specified in specifications.

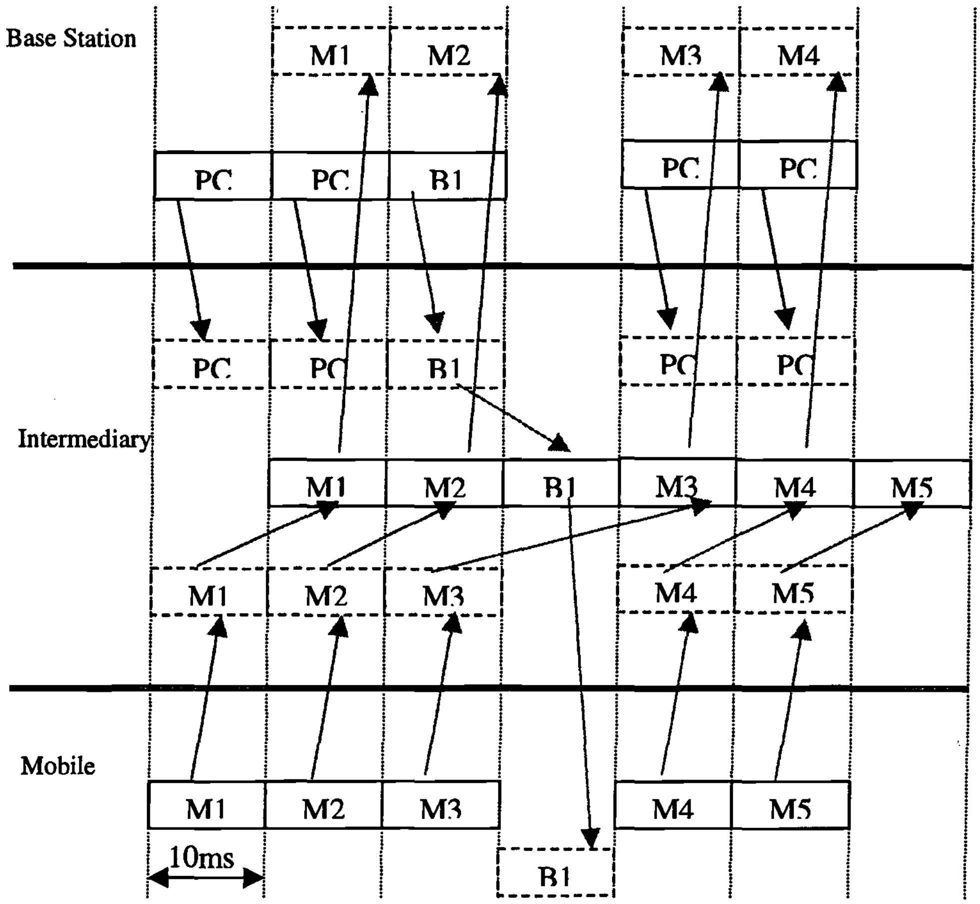


FIGURE 5.8: FDD_TDD Asymmetric Model

5.1.4. TDD-FDD Models

In this model TDD is used in upper arm and FDD in lower arm. The FDD and TDD operating frequencies are different and therefore the upper and lower arms use different frequencies. Like in other models, the same OVSF/Walsh code can be used for both uplink and downlink in both arms of the Stretched connection.

Since closed loop power is required in the lower arm for FDD mode, the unit of transmission is a frame, as the intermediary will have to calculate FER for downlink and verify FER for uplink of the lower arm. It should be noted that the frame structure for the lower arm is different from the upper arm in view of different modes of operation.

The intermediary has a dual receiver, with one receiver tuned to the uplink frequency of Mobile, while the other to the TDD frequency of the upper arm. The transmitter time multiplexes between upper and lower arms and uses the TDD frequency to transmit to base station in upper arm and the downlink frequency of Mobile for the lower arm.

The lower arm uses closed loop power control, while the downlink of upper arm uses closed loop and uplink of lower arm uses open loop power control, as required by the specifications [TDD-SIM].

5.1.4.1. Symmetric Model

A possible TDD-FDD symmetric model is shown in Figure 5.9. This model is similar to FDD-TDD model, with the functionality of the upper and lower arms reversed.

Applications:
UTRA: Voice and symmetric traffic
cdma2000: Not applicable

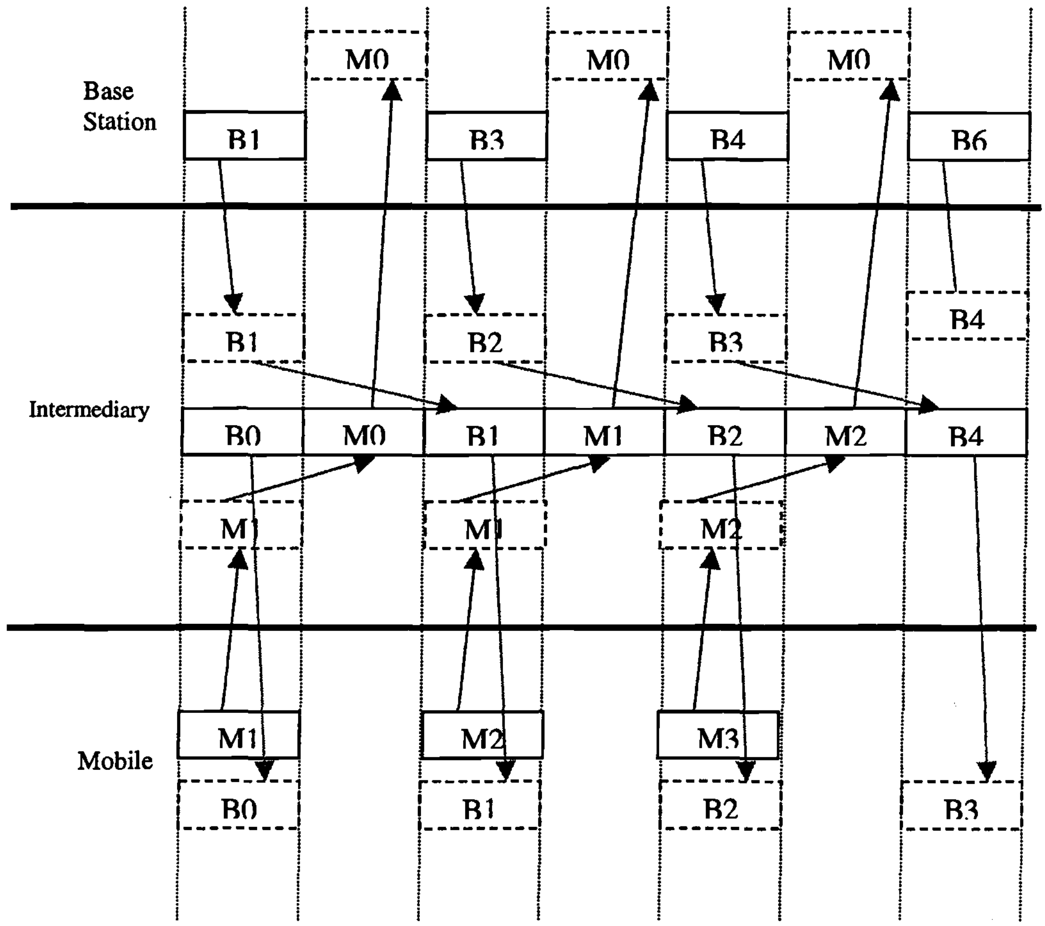


FIGURE 5.9: TDD-FDD Symmetric Model

5.1.4.2. Asymmetric Model

A possible TDD-FDD symmetric model is shown in Figure 5.10. This model is similar to FDD-TDD Asymmetric model, with the functionality of the upper and lower arms reversed. This model is more suitable for predominantly downlink transmission because the intermediary in the lower FDD arm has to transmit data and not power control updates. Like in FDD-TDD model, the propagation channel in a TDD arm, in this case the upper arm's propagation environment should change little so that the intermediary does not have to send power control updates to the Base Station. In case the propagation channel changes rapidly, then this model reduces to the Symmetric TDD-FDD model. Applications include Downloads and Internet browsing in UTRA. It is not applicable for cdma2000.

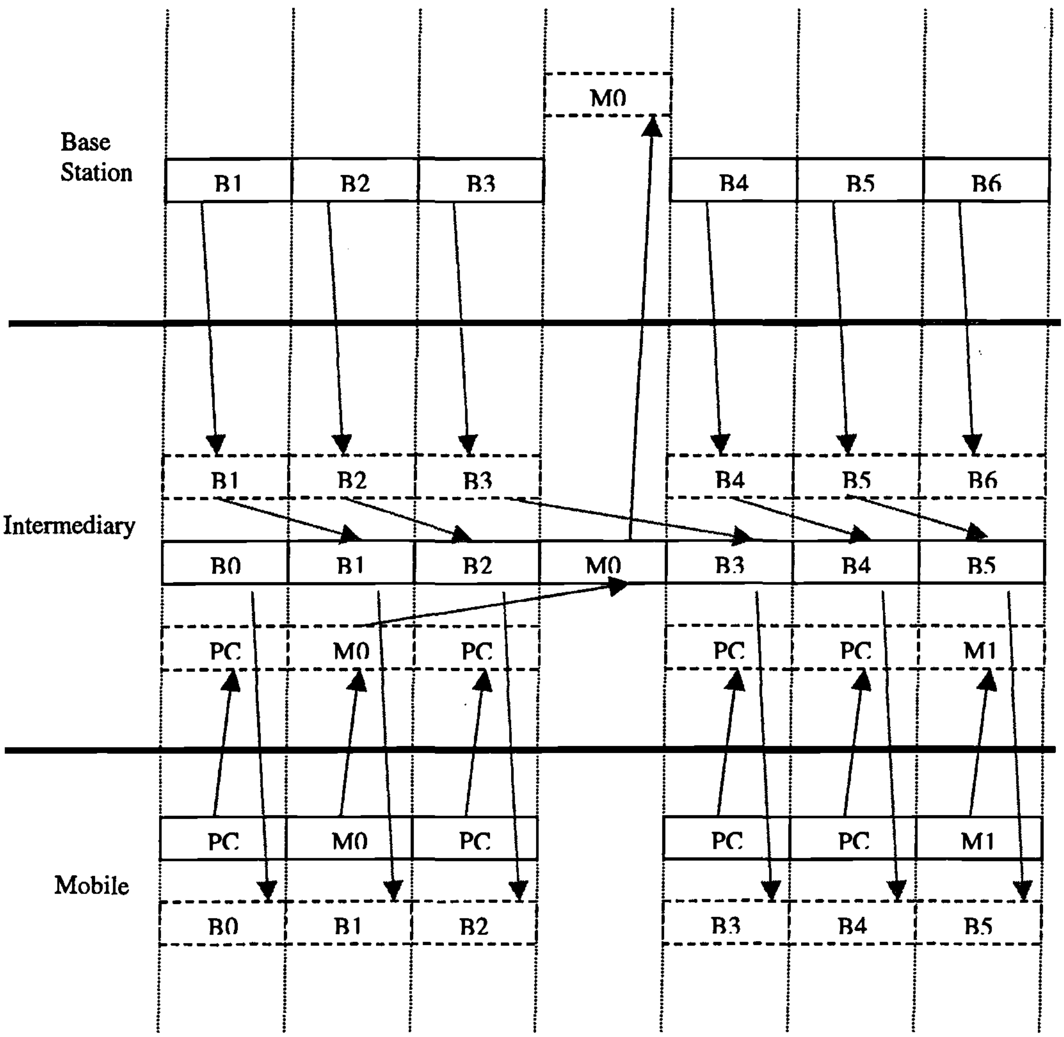


FIGURE 5.10: TDD-FDD Asymmetric Model

5.2. Unidirectional Models

For unidirectional stretched connection, either FDD or TDD duplex modes can be used in both uplink and downlink. If a combination of the duplex modes are used for the direct link and stretched links, i.e., TDD in direct arm and FDD in the stretched arms or vice versa, either the Mobile or Base Station or both have to use different duplex modes for uplink and downlink. Since the physical layer processing is different for FDD and TDD, using different modes for reception and transmission seems not feasible. The intermediary transmits only in one direction and so does not have to time multiplex transmission to BS and mobile.

If the uplink is stretched and downlink unidirectional, the mobile transmits to the BS through the intermediary. The data from the BS will not be sent to the intermediary, but directly to the MS. This has a "potential" advantage in FDD mode where the intermediary can continuously forward transmission to the Base Station, without having to transmit to the Mobile and thereby achieving higher connection throughput. But, the problem here is that the mobile should send power control updates to the Base Station, to control its transmission, as is required with closed loop power control mechanism in 3G standards. This means that the mobile apart from transmitting data to the Intermediary, should send power control information to the Base Station. Since the mobile is assumed to contain only one transmitter, now the Mobile has to time multiplex transmission to intermediary and Base Station, which thereby decreases the data transmission time of the Mobile. But, if the propagation environment is not changing, then the rate of power control updates can be decreased and higher throughput is possible.

Assume that the uplink was stretched and downlink direct, and that both stretched and direct connections operate in TDD mode. The functionality of the intermediary is similar to the previous case. Since the distances from the Mobile to Base Station and Intermediary are different, the timing synchronization is different for both. Since the mobile transmits to intermediary and receives from Base Station, synchronization between uplink and downlink transmissions in the Mobile is complicated because normally the distance from Base Station is much higher than the distance to the Intermediary. Therefore, the guard band has to be higher. Apart from that, uplink and downlink are not related at all. Moreover, the distances between them keep changing and this aggravates the synchronization problem between uplink and downlink.

5.2.1. FDD mode with Direct Downlink

A possible model is shown in Figure 5.11. This model is suitable for both symmetric and asymmetric models with low mobility. In this particular example, only the uplink has been shown with continuous data, while the downlink transmission from Base Station multiplexes transmission to the intermediary and the mobile. If we can replace the transmission of power control updates from Base Station with data frames, we can achieve higher data rates in the downlink. Similarly, if the power updates from the intermediary to the Mobile Station can be reduced, we can achieve higher data rates in the uplink. By achieving higher data rates in uplink and downlink, we can achieve higher data rates even for symmetric traffic. Two frequencies, one for the lower arm and the other for the upper arm and the direct call are required because the BS has to transmit power control updates to intermediary and data to the MS in case of symmetric traffic. The above observation is based upon the assumption that Closed loop power control is used for both direct and stretched connections. Instead, if open loop power control is used for the direct connection, then the Mobile need not send power control updates to the Base Station and thus higher downlink rates are possible. Open loop power control can be adopted in the direct downlink connection because orthogonal codes are used in the downlink and interference at the Mobile's receiver is not really bothersome.

Advantages: Symmetric higher data rates possible for low mobility environments and when open loop power control is used in the direct connection, because the intermediary, Base Station and Mobile do not have to send frequent power control updates.

Disadvantages: This model is suitable for low mobility models if the number of power updates to be transmitted by the intermediary to the MS has to be minimized. If the mobility of the intermediary or the Mobile increases, the propagation environment changes and so periodic power control updates have to be transmitted by the intermediary to the MS, decreasing the data rate proportionally. Also, even if just the mobile starts moving, the direct path also requires power feedback, which means that the Mobile has to transmit power control information to the Base Station. This overhead can be reduced, if the direct path uses open loop power control.

Applications:
UTRA-FDD and cdma2000: High data rate uploads or symmetric traffic like video conferencing in low mobility applications.

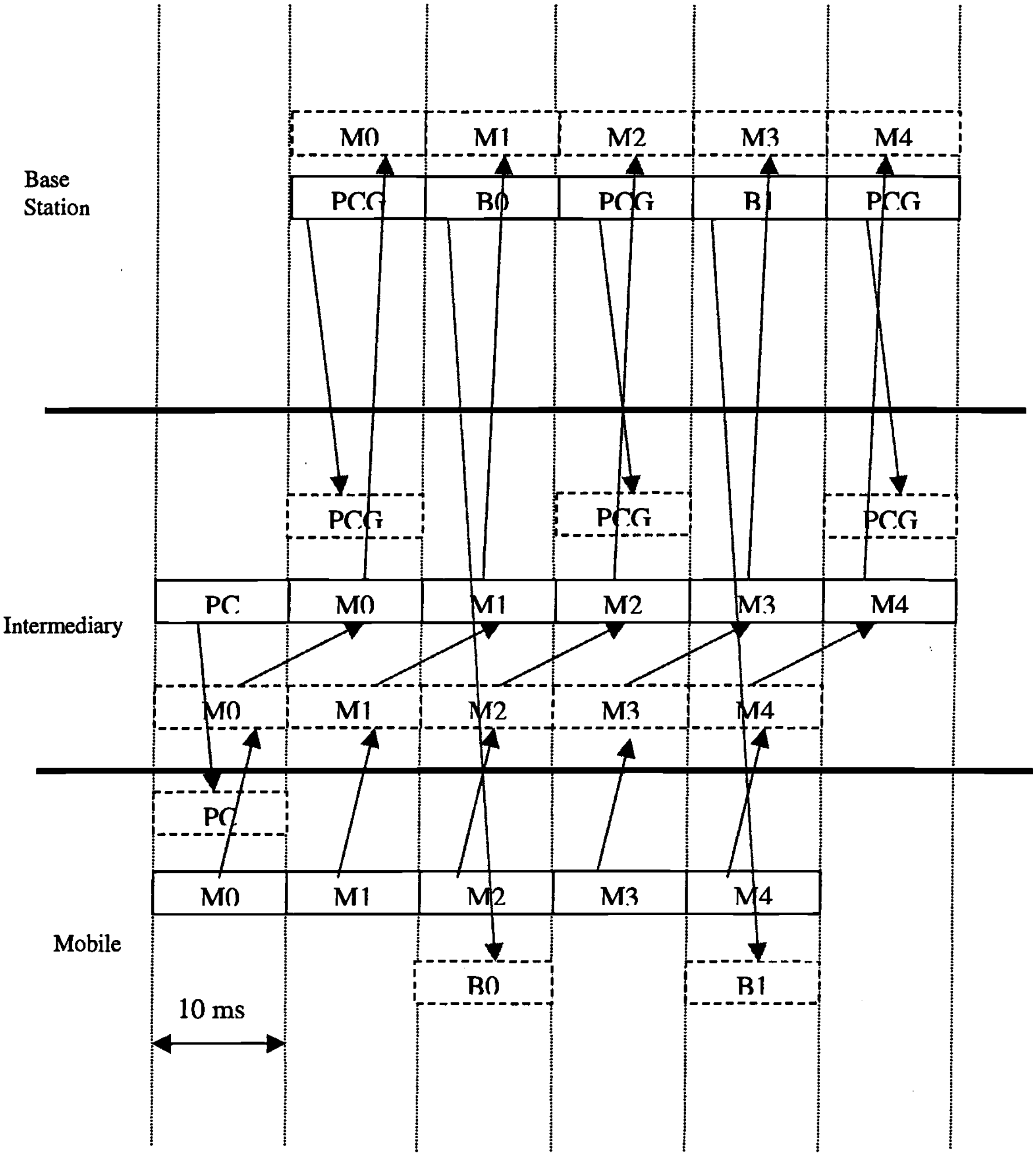


FIGURE 5.11: Unidirectional FDD Model with Direct Downlink

5.2.2. TDD mode with Direct Downlink

Since the mobile is in TDD mode, it has to time multiplex transmission to the intermediary and receiving from the BS. This model is suitable for short-range direct applications, because TDD mode requires accurate synchronization between the uplink and downlink. Since the MS has to interact with both the BS and intermediary, synchronization is difficult. Also, the problem is aggravated when either the MS or the intermediary is mobile. Therefore, these models are suitable only when the MS and intermediary are not mobile.

For symmetrical model, this is similar to Bi-directional Symmetric model for the Bi-directional TDD-TDD model. This is because the mobile has to time multiplex transmission to intermediary and receiving from the BS. The intermediary is idle when the mobile is receiving from the BS. Since the upper arm is used only for uplink, it is idle when BS is transmitting to the mobile. In terms of data rate, it is similar to TDD-TDD Bi-directional symmetric model.

But for asymmetrical predominantly uplink traffic, this model is similar to Bi-directional Asymmetrical TDD-TDD model because the mobile is continuously transmitting and so is the intermediary. The downlink from BS is rarely used. For asymmetrical predominantly downlink traffic, this model is similar to a Direct TDD model as the intermediary is rarely used in the uplink.

5.2.3. Unidirectional FDD & TDD models, with Direct Uplink

In this model, the mobile is transmitting direct to the BS and the intermediary is transmitting to the mobile. Normally, the direct connection is costlier than either the upper arm or lower arm and therefore, this model is not power efficient.

5.2.4. Other Unidirectional Models

The other models like TDD-FDD-FDD, FDD-FDD-TDD, TDD-FDD-TDD, FDD-TDD-FDD require that both FDD and TDD hardware implementations be simultaneously used in either BS or Mobile. I am not sure if this is feasible. I have heard of hardware implementations where both TDD and FDD implementations are present, but the mobiles can be used in either one of the modes at one time and not simultaneously.

5.2.5. Applications of Unidirectional Models

The advantages of unidirectional models are that high data rate is possible at low mobility. The intermediary does not have to time multiplex transmission between the BS and the node, but has to receive from one end and transmit to the other. Assuming that the intermediary can simultaneously receive and transmit at the same time when uplink and downlink frequencies are different, continuous unidirectional data traffic is possible.

In the Unidirectional models as we have seen above, the intermediary rarely transmits a power control update message to either the BS or the MS. In a mobile environment, this does not work. These models work only when the surrounding propagation environment does not change. When either the node or the intermediary moves, the propagation environment changes and power control updates have to be sent. This means that the intermediary will now have to time multiplex transmission of power control update messages along with the data, which decreases the data rate. Similarly, for the direct downlink connection, if the mobile is moving, it has to additionally send power control updates to the BS.

Therefore, the unidirectional models are only suitable for low mobility applications.

5.3. Choice of Model

The choice of the model is constrained by two factors

a. Single transmitter at the intermediary
b. If TDD mode is used in either the BS, intermediary or mobile, at any time, only transmission or reception is possible.

It is however assumed that the intermediary can receive and transmit simultaneously, i.e., it operates like in FDD mode. Also, it should have dual receivers so that it can simultaneously receive from both BS and MS. Operating the intermediary in TDD mode severely affects the performance, because it has to time multiplex transmission to BS, transmission to MS, reception from BS and reception from MS.

Due to the presence of only one transmitter in the intermediary, for symmetric traffic, the intermediary will equally time multiplex for upper arm and lower arm. This means that the receivers in BS and MS are not active all the time. Their transmitters can be active all the time, in which case, the intermediary receives continuously from both BS and MS and it has to either increase the coding rate or decrease the spreading and send two frames worth of data in one frame and thereby simulate continuous transmission and reception in BS and MS.

If either the BS or the mobile are in TDD mode, because they have to time multiplex reception and transmission, compared to direct FDD mode, their transmission and reception duration are less.

Due to the decrease in propagation distance by using the intermediary, lower spreading or higher coding rate can overcome the limitation of single transmitter in the intermediary, and at least achieve data rates possible as in direct connection. Because the propagation loss decreases by the square root of distance in normal cases, the spreading can be reduced by more than half and thereby data rates higher than the direct connection is achieved.

In FDD-TDD and TDD-FDD modes, the symmetric traffic is similar to that of basic FDD-FDD modes. This is because, the transmission time and reception time is limited by the presence of single transmitter in intermediary.

For asymmetric traffic, the FDD-TDD and TDD-FDD modes are the most attractive because both limitations mentioned above are avoided. The TDD device is continually transmitting to the intermediary, which it continuously forwards to the other side, without having to transmit power control information. Therefore, these models give the highest data rates possible for asymmetric traffic.

Also, for asymmetric traffic, the choice of using a TDD-FDD or a FDD-TDD model depends on whether the intermediary is spending time transmitting data or power control updates. When the intermediary spends most of its time transmitting data than transmitting power control updates, it is efficient. Power Control updates are control information. For a predominantly uplink traffic, FDD-TDD mode and for a predominantly downlink traffic, TDD-FDD mode gives highest data rates, as in each case the intermediary is predominantly transmitting data.

In both FDD-TDD and TDD-FDD modes, the FDD device is not simultaneously receiving or transmitting and therefore, the spectrum is wasted.

In TDD-TDD mode, predominantly uplink traffic is efficient. This is because, the downlink uses closed loop power control and therefore the intermediary and the mobile should update the Base Station and Intermediary respectively for a predominantly downlink transmission. But, since uplink uses open loop power control, for a predominantly uplink transmission, the Mobile and the intermediary spend most of their time transmitting data rather than power control updates. Since at least one slot has to be used for downlink, the received power of the downlink transmission can be used to adjust the uplink transmission as is done in open loop power control mechanisms. Again, this model is suitable for low mobility scenarios, otherwise, power control updates should be sent in the downlink more frequently. For asymmetric traffic, this model is spectrally efficient because BS or MS are continuously receiving or transmitting. It should be noted though that both arms of the stretched calls require different frequencies.

For Symmetric or Asymmetric high data rate applications with low mobility, unidirectional models can be used, as the intermediary in this case needs to transmit to either the BS or the Mobile and so continuous transmission is possible. Since increase in mobility requires transmission of power control information, these unidirectional models act like Bi-directional models when mobile or intermediary starts moving.

It is assumed that the mobile and intermediary have TDD and FDD capable hardware. As mentioned above, not one model is suitable for all applications – symmetric or asymmetric. Therefore, depending on the applications, a suitable model can be adopted to use the spectrum efficiently.

Table 1 and Table 2 summarize the properties of each Model. Table 1 summarizes the Bi-directional models and Table 2 summarizes the Unidirectional models.

Model	Low Mobility	High Mobility
FDD-FDD Symmetric	Good, but limited by intermediary	Good, but limited by Intermediary.
FDD-FDD Asymmetric	Very good, but spectrum is wasted	Not good. Intermediary has to send PC's
TDD-TDD Symmetric	Good, but limited by Intermediary	Not good. Synchronization problem
TDD-TDD Asymmetric	Very good	Not good. Synchronization problem
FDD-TDD Symmetric	Good, but limited by intermediary	Not good. Synchronization problem in TDD arm
FDD-TDD Asymmetric	Very good, spectrum wasted in FDD	Not good. Synchronization problem in TDD arm
TDD-FDD Symmetric	Good, but limited by Intermediary	Not good. Synchronization problem in TDD arm
TDD-FDD Asymmetric	Very good, spectrum wasted in FDD	Not good. Synchronization problem in TDD arm

Table 1: Bi-Directional Models

Model	Low Mobility	High Mobility
FDD-FDD Symmetric	Very good, spectrum is Wasted for unused arm in stretched connection.	Not good. Mobile has to send PCs.
FDD-FDD Asymmetric	Very good, similar to other. Spectrum is wasted for unused arms.	Not good. Intermediary has to send PC's
TDD-TDD Symmetric	Good, limited by Mobile	Not good. Intermediary & Mobile have to send PC's
TDD-TDD Asymmetric	Very good for uplink, similar to other Asymmetric models.	Not good Synchronization problems
FDD in Direct and TDD in Stretched	Not suitable. BS and Mobile require both TDD and FDD circuitry to be active at same time.	Not suitable. Circuitry and Synchronization problems.
TDD in Direct and FDD in Stretched	Not suitable. BS and Mobile require both TDD and FDD circuitry to be active at same time.	Not suitable. Circuitry and Synchronization problems.

Table 2: Unidirectional Models

5.4. Optimization with Unequal Upper and Lower Arm Lengths

In these models either the spreading is decreased or coding rate increased for the shorter arm and simultaneously, either the spreading is increased or coding rate decreased for the longer arm. The relative lengths of the upper and lower arms of stretched calls vary dynamically. If the length decreases, then the transmit power required to satisfy the SNR at the receiver at the current data rate decreases. Instead of decreasing the transmit power, if the spreading rate is decreased or the coding rate is increased we can achieve higher data rates with the same number of slots.

Suppose we have a fixed data rate that has to be supported with a stretched connection and that we are using one of the stretched models of Section 5.1 and 5.2. Assume that the lengths of the upper and lower arms are not the same. The spreading rate used for the connection is the spreading rate that is required for the longer arm of the stretched connection. But, as one of the stretched arms become shorter, then the SNR increases above the threshold and therefore, we can decrease the transmit power or increase the Processing gain so that we just satisfy the required SNR levels. Instead of decreasing the transmit power, we can increase the Processing Gain (PG), and by doing so, we are basically sending more data in each slot. Since we have assumed that the data rate for a frame is fixed, by increasing the processing gain, we require less number of slots to transmit the data. For the other arm, which is getting relatively longer, we require higher transmit power or higher spreading rate to overcome the increase in propagation distance. Instead of increasing the power level, we can decrease the processing gain and utilize the slots vacated by the shorter arm. Thus, we see here that more number of slots is utilized for transmission to the longer arm and less number of slots is utilized for transmission to the shorter arm. The amount of power that we save by this arrangement has to be further evaluated.

An example explaining the use of unequal distribution of data rate for symmetric traffic is shown in Figure 5.12. Here, spreading in upper arm is decreased because the upper arm is shorter, while spreading is increased in the lower arm because the lower arm is longer. Alternatively, for the shorter arm, the coding rate can be increased and for the longer arm, the coding rate can be decreased.

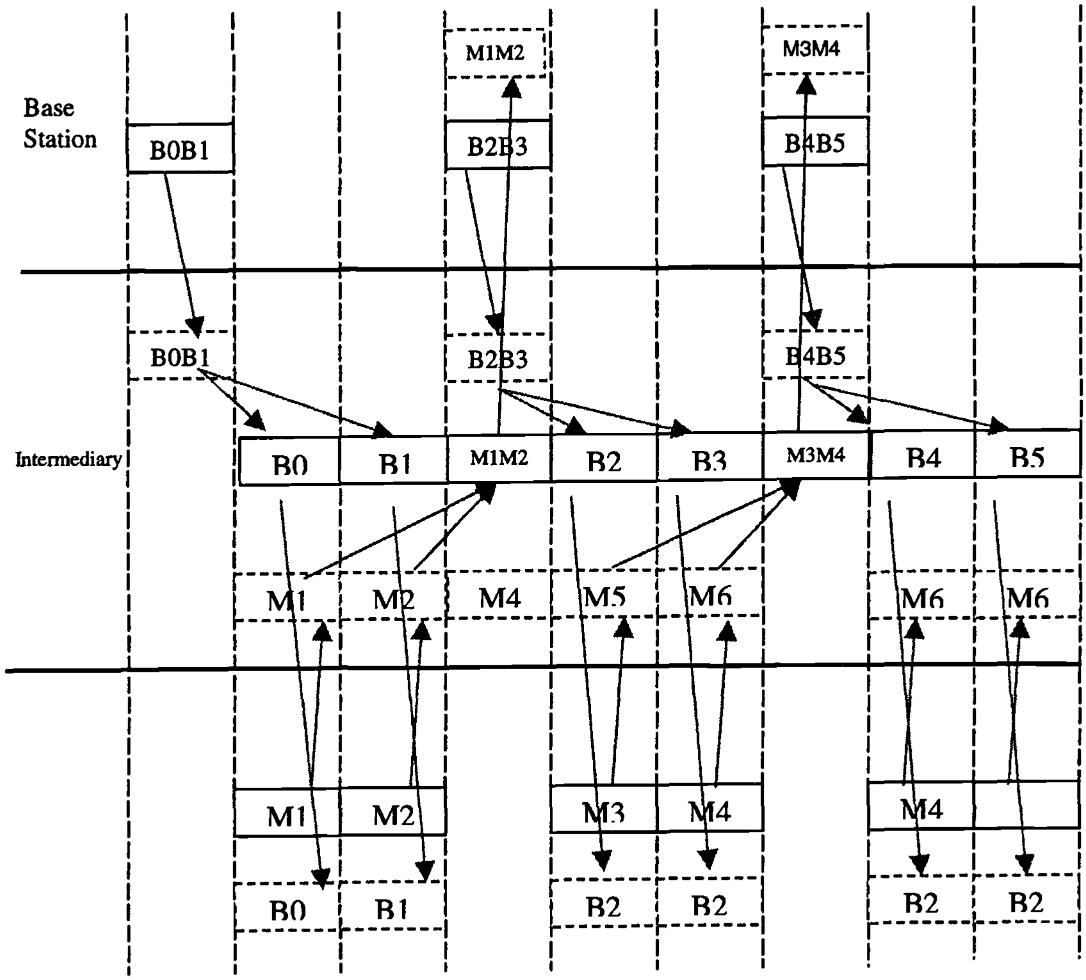


FIGURE 5.12: Optimized Stretched Call

6. SIMULATOR SETUP

The simulator is modeled on a discrete event based simulation technique. Changes in state of the node and the base station take place in response to events. The simulator is a single threaded application implemented in Java. The simulator implements Call Model, Mobility model and Propagation Model.

6.1. Simulation Layout

The simulation layout is a GridLayout. Each grid denotes a block of size X meter*Y meter, with X and Y being variable. Example block sizes are 50m*50m, 100m*100m, 200m*200m etc., the number of grids in the simulation also being variable.

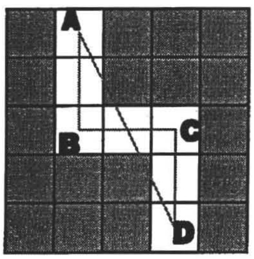
The Simulation layout contains traversable grids and non-traversable grids, denoting obstructions like buildings. To simulate mobility, intersections are introduced. Nodes are initialized from a random intersection. Intersections assign direction and velocity to each node, whenever it initializes a node or when a node crosses it. Direction and velocity need to be set for each intersection at the beginning of the simulation. By varying the velocity and direction, highway, downtown, suburban and other mobility patterns can be simulated. Base Stations can be placed on buildings, intersections or on any of the traversable grids.

6.2. Propagation Model

The propagation model implemented is a Recursive model specified in UMTS specifications for vehicular and pedestrian environment in an urban area. This model is explained in Section 3.1 above.

The breakpoint is assumed to be 300 meters and frequency as 1900Mhz. The standard deviation of lognormal fading is 2.5dB for a power-controlled system.

This model requires that a shortest path be found between the source and target in free space. When the source and target are in Line of Sight (LOS), the shortest path is a straight line between them. The path loss is proportional to the length of the path. When the source and target are in Non Line of Sight, then according to the model, this can be simulated as a combination of Line of Sight segments. The path loss then is not only affected by the length of each of the line of sight lines, but also the angle between the lines. The smallest angle in clockwise and anti-clockwise directions is considered and the minimum angle is 0 degrees and the maximum angle is 90 degrees. In the example below, the path loss between A and C is due to segments AB, BC and CD and also due to the angles between segments (CD, BC) and (BC, AB).



The procedure to find the path loss begins by identifying the grids, which are traversed by the path. Then, Line of Sight segments are identified. To find out the end points of each segment, we begin with the start grid and move to its adjacent grid in the path and check if the start grid is visible. If so, we move to its adjacent grid in the path and again check if the start grid is visible. We follow this procedure until we come to grid such that the start grid is not visible. The previous grid is the end point of the first segment. So, in our example above, B is the farthest grid, from which the start grid A is visible. We now make B the start grid and following the same procedure, we find that C is the farthest visible grid from B. Similarly D is the farthest visible grid from C, which also happens to be the target grid. By doing so, we get the shortest path. The angles between the segments in every turn are noted and using the Recursive formula, we find the path loss from A to D.

This formula can be used to pictorially display the path traversed by the radio signal. The path loss between a traversable grid and every other traversable grid is found out and stored in a SQL table for future reference.

6.3. Call Model

The arrival of calls at the Base Station is modeled as a Poisson distribution, with inter-arrival duration modeled as an exponential distribution. The duration and interval between calls are variable factors.

6.4. Mobility Model

The node mobility is modeled as a Gaussian distribution. The mean velocity is a variable factor with the standard deviation equal to 10% of the mean. We consider here a one-lane highway. The mobility is assumed as a Gaussian distribution because most of the vehicles travel at the mean velocity, with few traveling at higher or lower velocities.

7. SIMULATOR DESIGN

In this section, the Simulator design is explained. As mentioned previously, the Simulator is based on Discrete-Event based simulation. Section 7.1 describes the major classes of the simulator. Section 7.2 describes the Base Station state machine and Section X.3 describes the Node state machine. A detailed description of design and implementation of the Simulator is part of Portland State University's thesis.

7.1. Simulator Classes

The major classes of the Simulator are classified as

1. Layout Building classes
2. Network Element classes
3. Event classes
4. Energy Measurement class
5. Event Scheduler

The Layout Building classes construct the terrain, calculate the path loss either between any two points or between one grid and every other grid in the terrain and store it in a SQL table. Nodes and Base Stations represent the network elements and each are defined as object. The network elements generate and handle events, represented by the Event classes. There is a Measurement class that calculates the energy spent by the system and by individual nodes. Event scheduler is the main event-scheduling machine that accepts events and assigns them to the destined instance of a network element.

7.2. Base Station State Machine

The Finite State Automata of a Node in the Base Station is shown in the Figure 7.1 below.

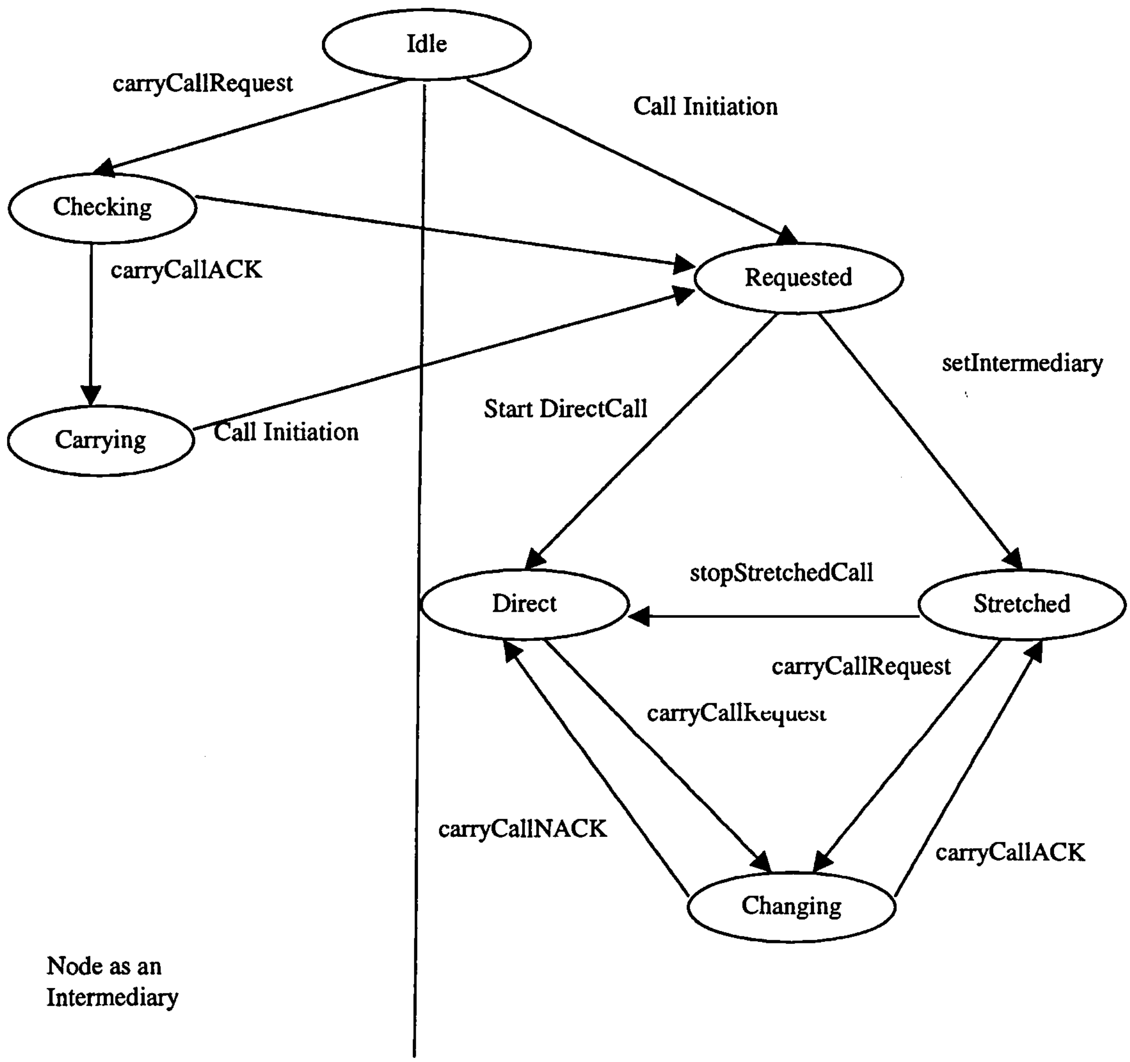


FIGURE 7.1: Base Station State Machine

When a node powers on or enters into the cell, it sends a RegisterToBS event. The node state in the BS for the new node is Idle. When the node wants to make a call, it sends a callInitiation Request to the BS. The state changes from Idle to Requested. The BS now tries to find an intermediary for the node. If it successfully finds an intermediary it sends a setIntermediary event with IntermediaryID to the node, it changes the state of the node from Requested to Stretched. In case it was unsuccessful in finding a suitable intermediary, it sends a startDirectCall Event, which changes the node state to Direct. When the node state is stretched and either the node or the intermediary moves causing a change in the propagation environment, the intermediary needs to be changed. When the BS is finding a new intermediary for the node, the state of the node changes from Stretched to ChangingIntermediary state. Once the possible intermediary, which the Base Station has requested to be an intermediary with a CarryCall event returns with a CarryCallACK, the state of the node is changed from ChangingIntermediary to Stretched again. If the intermediary is not found and the direct call is the best call for the node, the state of the node is changed to Direct from ChangingIntermediary.

Within duration of the call, there can be many transitions between stretched and direct via changingIntermediary state because a suitable intermediary was not found for some time. The node might always be in a stretched connection, with the transitions taking place between stretched and changingIntermediary repeatedly, as and when a new intermediary is found.

When the node is idle, it periodically scans the walsh codes of all the active nodes. The BS broadcasts the walsh codes periodically and the nodes measure the signal strengths and report the measurements to the Base Stations. The BS selects a node as a possible intermediary and sends a carryCallRequest to the intermediary. The node state in the BS changes from Idle to CheckingIntermediary state. In case the node does not make a call at that instant, it will accept the request and send a carryCallACK. The node state changes from CheckingIntermediary to carrying state. A call gets terminated when the node sends a callTermination request. The current state of the node can either be direct, stretched or changingIntermediary state. Correspondingly, the state of the intermediary node in the Base Station can be checkingIntermediary or carrying. The state of the node in the BS becomes Idle. The Base Station then sends a terminateStretchedCall event to the intermediary node and changes its state in the Base Station also to Idle. When the intermediary node is in checkingIntermediary state or carrying state, it might send a callInitiation request. When this happens, the state of the carried node is immediately changed to Direct, by sending a stopStretchedCall event. The Base Station then begins the process again of finding the best intermediary to the node.

7.3. Node State Machine

The different states and the transitions of a node object is shown below in Figure 7.2. The node powers on to be in Idle state. In Idle state, it is continuously scanning the broadcast channels to retrieve the Walsh codes of other active mobiles, which are in Direct Connection Mode. It periodically sends the signal strength of for these mobiles to the Base Station.

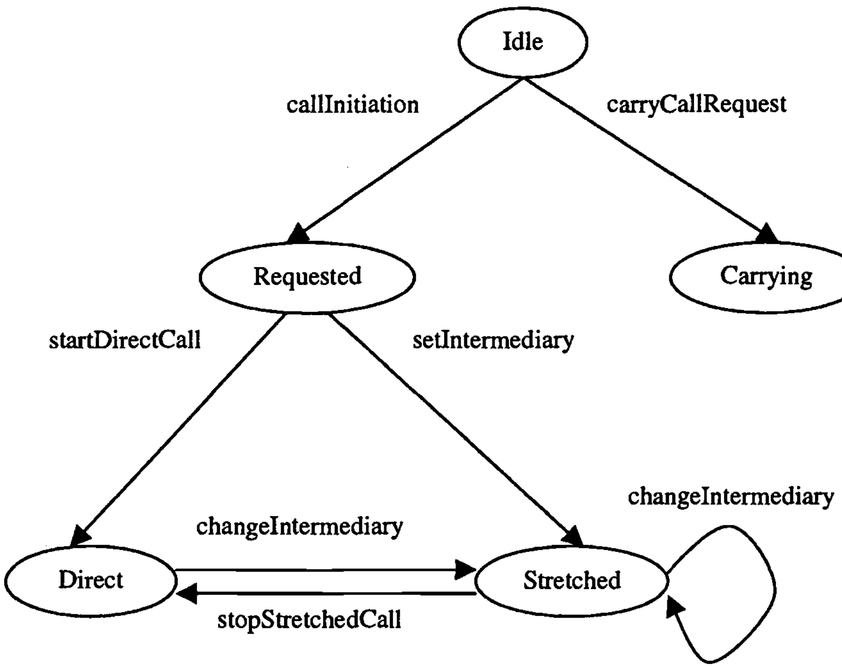


FIGURE 7.2: Node State Machine

When the mobile gets a callInitiation event, its state changes from Idle to Requested and sends an updateToBS event, with a callState change information. It waits from the Base Station for either startDirectCall event or the setIntermediary event. The Base Station sends a startDirectCall event when it was unable to find a suitable intermediary for the mobile because the direct connection was more economical than any of the possible stretched connections. On receiving the startDirectCall event, the node state changes from Requested to Direct and the call begins. Later, the BS might find a suitable intermediary, in which case, the BS sends a changeIntermediary event with the intermediary event, and the node state changes from Direct to Stretched.

If the Base Station was able to find an intermediary, it sends a setIntermediary event with the identifier of the intermediary. The node state changes from Requested to Stretched. While being in the Stretched state, the BS might find another intermediary, through which the stretched connection is more economical. The BS sends a changeIntermediary event with the identifier of the new intermediary. Alternatively, the BS might send a stopStretchedCall event for 2 reasons. First, if the intermediary of the mobile gets a callInitiation request, in which case the stretched connection should be immediately stopped and the mobile is directed to use the direct connection. The BS immediately begins the process of finding a new intermediary for the mobile. In the mean time, direct connection is used, even though it is costlier. A second reason for the BS to send the stopStretchedCall event is when the direct connection is the most economical.

When a callTermination event is received, the node state changes either from Direct or Stretched to Idle. It is possible that when the node is in Requested state a callTermination event is received, in which case, the node state changes to Idle.

The node call state changes from Idle to Carrying, when the Base Station sends a carryCallRequest event. This event is positively acknowledged most of the time except in the rare occasions when a callInitiation request occurs for the node at the same time or within one second. If the node can carry a call, its state is changed from Idle to Carrying. In node is not able to carry the call, if the carryCallRequest came when the node's call state was Requested. Since the Base Station is always updated with changes in the node call state, carryCallRequest is not sent when the node state is Direct or Stretched.

8. STRETCHED CONNECTION HANDOFF

8.1. Soft Handoff Mechanism for a Stretched Connection

The principle of soft handoff involving multipath and RAKE receivers is adopted for stretched connection as well. It is assumed for the stretched connection that the mobile is always connected with the Base Station. This is required for the least reason that when the intermediary itself wants to initiate a call, then the stretched connection must be immediately terminated. To prevent the mobile's connection from getting disconnected, the direct connection is always required as a backup. When the mobile is in stretched connection, its connection with the Base Station is in dormant state, which can be activated quickly when a direct connection is required. The re-activation is quick because no call initiation with the Base Station is required again.

In the normal soft handoff scheme, the handoff is mobile-controlled. It means that the mobile periodically listens to the pilot channels of the neighboring base stations and when the signal strength of the one such pilot increases above the required threshold to be part of the active set, the mobile sends a pilotStrengthMeasurement event with the identifier of the neighboring base station. When the parent's base station pilot signal strength goes below the threshold, the mobile sends another pilotStrengthMeasurement event to the parent and the handoff is initiated to the other base station, which is still in the active set. The soft handoff procedure requires that the mobile to know the identifiers of the base station and to actively measure their pilots.

If similar procedure has to be followed for handoffs between intermediaries, there are many disadvantages.

a. The mobile should now know the identifiers of the intermediaries
b. The mobile should actively listen to their pilots apart from listening to the neighboring Base Station's pilots.
c. The intermediaries must now continually transmit the pilot, which will drain their battery power.
d. As the number of intermediaries increase in the vicinity of the mobile, the duration of the most power efficient stretched connection decreases, thereby increasing the number of handoffs. The mobile must dynamically be updated with the identifiers of the intermediaries in the vicinity of the mobile, so that the mobile can measure their pilots.
e. Pilots of the intermediaries have to be uniquely distinguishable and therefore require additional orthogonal codes called as pseudo Walsh codes, to distinguish from the Walsh codes used by the base stations.
f. If the intermediaries have to continually transmit the pilot, then the forward interference increases, because the pseudo Walsh codes are not completely orthogonal.

Therefore, the use of soft handoff technique in the handoffs between intermediaries is costly and power inefficient. Thus, a new handoff technique is required.

8.2. Intermediary Controlled Soft Handoff

A node needs always need to be registered with at least one base station. This is required when the node initiates a call or when it terminates a call (the node is the called party). The location of the mobile is required, for example when a call terminates at the mobile. Therefore, the mobile is required to be always reachable to and from the Base Station. Even in idle mode, when it moves to a neighboring cell, it should initiate a handoff to the neighboring Base Station. This is possible only when the mobile is powered on.

Assuming that the node is in contact with a base station always, the argument here is that the mobile need not know the identifier of the intermediary, instead the intermediaries needs to know the identity of the mobile. The intermediaries can in idle mode listen to the transmissions of the mobile. The mobile need not transmit the pilot and by knowing the location of the mobile from the Base Station, the intermediaries can synchronize their receiver to start listening to the mobile's transmission, by adjusting the delay. Once the mobile's transmission crosses the threshold required to be in active set, the intermediary can notify the Base station. If there is more than one intermediary, each intermediary reports periodically the signal strengths of the mobiles in their vicinity.

In UMTS for example, the Base Station periodically broadcasts the dynamic list of scrambling codes (which do not have any security significance in UMTS) of the mobiles, which are seeking an intermediary. The intermediaries listen to these broadcasts and then tune their receiver to the Mobile's transmit frequency and load their receiver with the mobile's scrambling code and do the measurement. The Base station in the broadcast can pass any phase and location information required to tune to the mobile. The intermediaries then periodically report to the Base Station and the Base Station based on reports from multiple intermediaries in the vicinity of the mobile, selects the best intermediary. The choice of how the intermediary is selected is out of scope of this thesis.

In cdma2000, voice communication is not possible because of physical layer security. For data, the phase offset can be transmitted to the intermediaries, using which they can load their long PN sequence generators with the offset and be able to de-correlate the Mobile's signals.

Once the Base Station selects the intermediary, the intermediary can start listening to the BS transmission, using the same Channelization and scrambling code used for the mobile. The delay offset for the mobile changes for each intermediary. Since we are assuming that mobiles will be GPS supported, the BS has to transmit the exact location of the mobile during the broadcast. Therefore, the intermediaries know the exact distance between them and the node. With this, the delay offset of transmission of the intermediary can be adjusted to make it appear to the mobile, that the intermediary transmission is actually a transmission from the Base Station. It should be noted that the delay offset is in terms of chip durations.

Alternatively, the search window of the mobile can be dynamically varied so that varying delay spread from the intermediaries can be accordingly handled.

Two factors can vary with an intermediary handoff.

a. Coding rate
b. Search window size.

During the handoff, two intermediaries will be actively transmitting to the mobile. The BS decides the instant the new intermediary will start transmitting. From that instant to the time the old intermediary is in the active set, the old intermediary can also transmit to the Mobile along with the new intermediary. If the new intermediary is much nearer than the old intermediary, then the new intermediary can use higher coding rates. To maintain uniformity, the old intermediary is also supposed to use the higher coding rates. But, by doing so, the old intermediary's processing gain will decrease and therefore, the SNR will decrease. Therefore, the old intermediary will go out of the active set fast. It the coding rate for the old and new intermediaries remains the same, then the old intermediary can continue to receive and transmit until the mobile's signal strength falls below the active list threshold.

The search window size required at the mobile varies depending on the physical distance between the intermediary and the node. Even if the distance of the new intermediary is farther than the old intermediary, the signal strength from the mobile might be stronger, because the new intermediary might be at LOS with the mobile and the old intermediary is at NLOS. So, the search window size can either increase or decrease when the new intermediary takes over.

There are many advantages of the Intermediary controlled soft handoff. They are:

a. The mobiles need not know the identity of the intermediaries.
b. The receiver of the mobile still listens to the BS and the intermediary transmissions are like multipath components of the BS. The handoff is taken care by the intermediaries. Therefore, this handoff scheme is called as intermediary controlled handoff.
c. The intermediaries are not transmitting their pilots and energy is conserved and also decreases the interference level

9. RELATED WORK

The 3rd Generation Standards of UMTS [UTRA] specify a mechanism of multi hop connection between Base Station and Mobile called as Opportunity Driven Multiple Access (ODMA). The intermediaries here are other Mobile Stations. This can be a multi-hop. In this scheme, each Mobile maintains connectivity table of Mobile Stations in its range. It can maintain up to 5 neighboring mobiles in the list. If there are more than 5 neighbors, then it filters the best of five using data rate and transmit power as the metrics. Initially, the Mobile will not have any member in the connectivity table. It broadcasts a probe packet periodically and the neighbors respond with their identity and the data rate and power level required to reach them. The Mobile upon receiving the response sorts them based on first the data rate and then the power level. This is how it constructs its neighboring nodes.

ODMA requires periodic broadcast of probe packets and maintenance of the connectivity table. Frequent probing and maintenance requires additional computing in the Mobile and also costs additional power consumption in the mobiles. The mobiles need to know the neighbors. ODMA forms an ad-hoc network of nodes.

Our scheme is a two-hop mechanism compared to multi-hop mechanism of ODMA. Also, in our scheme, the Mobiles need not know its neighbors and handoffs take place seamlessly by just adjusting the search window sizes. The intermediaries are decided by the Base Station, which has a database of all the nodes in its domain. The advantage of letting the Base Station choose the intermediary is that the Base Station has the knowledge of the velocity, direction of motion of both the Mobile and Intermediary, based upon which the Base Station can optimize and select the best Intermediary which can serve the Mobile for a long period of time.

Another important advantage of our Stretched Connection model is the delay is not variable. The reason is that we have only one Intermediary. With ODMA, the number of intermediaries can vary, and therefore the end-to-end delay varies, which is not suitable for real time applications like voice and video conferencing, which are delay sensitive. Adding more number of intermediaries increases the delay proportionally and should be as minimal as possible.

10. APPLICATIONS

Whenever the transmit power of the Mobile has to be decreased, a Stretched Connection can be adopted. As we have seen, not one single Stretched Connection Model is suitable for all the applications. Table 1 and Table 2 give the best models for different types of services. By adopting suitable Stretched Connection models, we can get high throughput for all types of services.

A stretched connection is more valuable when the Mobile has less battery life. If another Mobile is chosen as an intermediary, the life of its battery decreases. But, for example, if an intermediary is chosen only when it is in Line of Sight distance from the Base Station, then the Intermediary requires a minimal amount of energy. The Mobile's range is also decreased, and due to the non-linear power distance relationship, the decrease in power is significant. If the Mobile is in the edge of a cell, then a car can be used as an intermediary and since a car is assumed to have enormous amounts of energy, battery life of the car is not a factor.

More specifically, a stretched connection is very valuable when the Mobile is in a dead zone for a brief time, where the Base Station's signal is non-reachable. In these cases, using an intermediary, who is at Line of Sight to the Base Station, enables the Mobile gain a connection with the Base Station.

11. CONCLUSION

A stretched call is a two-hop connection between the Mobile and the Base Station made possible by the introduction of an intermediary. Due to the shorter propagation distances of the two hops, the transmission power required for each hop is reduced. Due to the non-linear relationship between Power and distance, the cumulative transmission power from both arms of the stretched connection is much lesser than the direct connection.

An Intermediary is more than a repeater and actively involved in the handoff procedures and signal measurement. Another mobile, or a car, or a network element in the Network Infrastructure of a 3G Wireless Network can be an intermediary.

The salient features of CDMA and the physical layer processing of the 3G networks have been briefed upon in this thesis.

In developing the stretched call architecture, we have taken into consideration the duplex modes, security, relative lengths of the two arms of the stretched connection, traffic symmetry, direction and propagation environment. We have proposed many possible Stretched Connection architectures and their applications. We have seen that Bi-directional FDD-FDD mode is suitable for Symmetric traffic, while Bi-directional TDD-FDD and Bi-directional FDD-TDD and Unidirectional FDD-FDD modes are all suitable for Asymmetric traffic.

Due to the mobility of the Mobile Station and Intermediary, the number of handoffs increases. We have proposed an alternative intermediary initiated handoff mechanism, which reduces the overhead on the Mobile Station to carry out the handoff procedures. Also, the Mobile Station is not aware of the intermediary's identity.

cdma2000 is not suitable for Stretched voice communications because of implementation of voice privacy at the physical layer. On the other hand, data communications is still possible. In UMTS, both voice and data communications are possible with Stretched Connections. A delay of twice the frame duration is introduced due to processing at the intermediary. But, this delay is tolerable.

Finally, we have explained the design of a Discrete Event based Simulator which we have implemented to simulate our Stretched Call architecture. We have shown the new control procedures required to enable a Stretched connection.

We have therefore demonstrated that using the existing 3G architecture, we can support a Stretched connection, with no change in hardware but with new control procedures required.

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