Intuitive Guide to Principles of Communications
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Code Division Multiple Access (CDMA)

The Concept of signal spreading and its uses in communications

Let's take a stright forward binary signal of symbol rate 2.

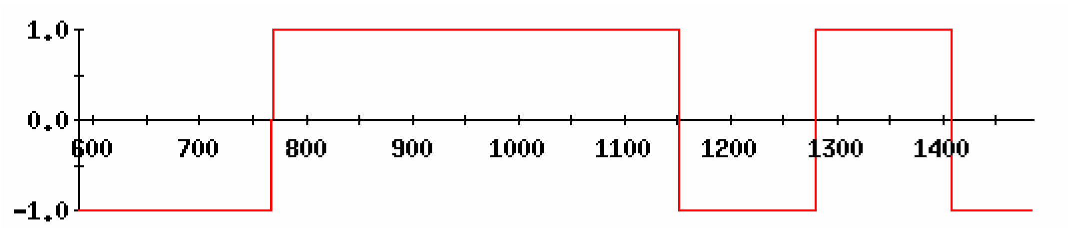


Figure 1 – A binary information signal

To modulate this signal, we would multiply this sequence with a sinusoid and its spectrum would look like as In figure 2. The main lobe of its spectrum is 2 Hz wide. The larger the symbol rate the larger the bandwidth of the signal.

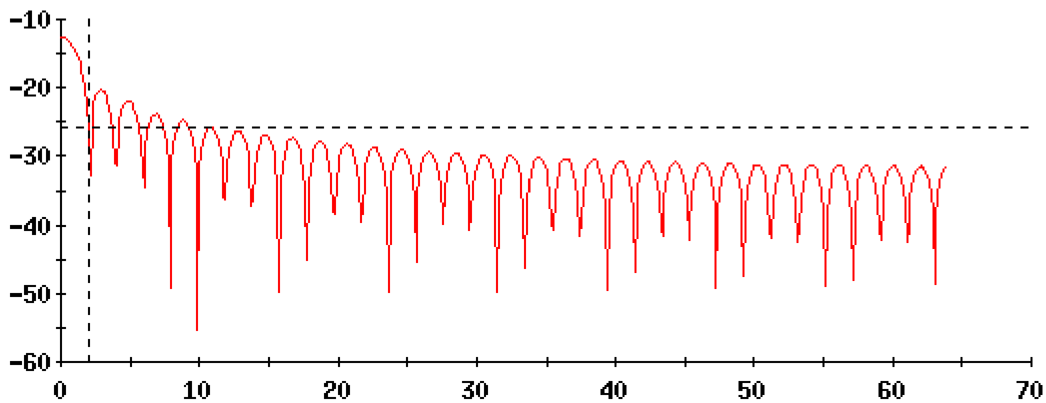


Figure 2 – Spectrum of a binary signal of rate 2 bps

Now we take an another binary sequence of data rate 8 times larger than of sequence shown in Fig. 1.

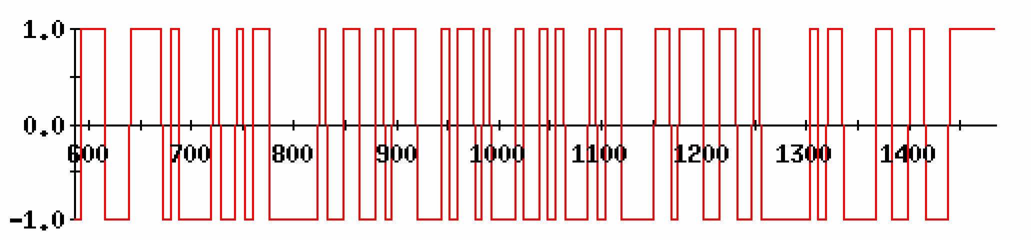


Figure 3 – A new binary sequence which will be used to modulate the information sequence

Instead of modulating with a sinusoid, we will modulate the sequence 1 with this new binary sequence which we will call the code sequence for sequence 1. The resulting signal looks like Fig. 4.

Since the bit rate is larger now, we can guess that the spectrum of this sequence will have a larger main lobe.

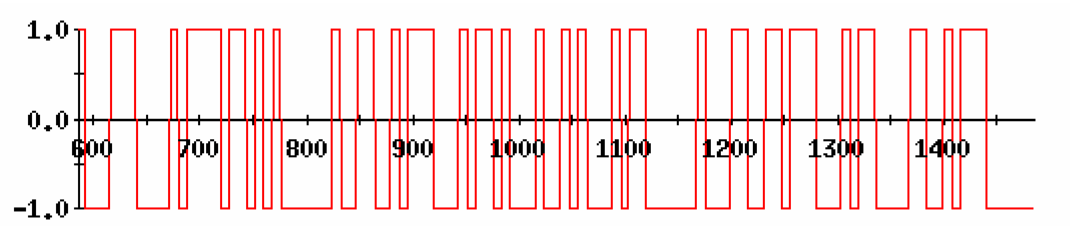


Figure 4 – Each bit of sequence 1 is replaced by the code sequence

The spectrum of this signal has now spread over a larger bandwidth. The main lobe bandwidth is 16 Hz instead of 2 Hz it was before spreading. The process of multiplying the information sequence with the code sequence has caused the information sequence to inherit the spectrum of the code sequence (also called the spreading sequence).

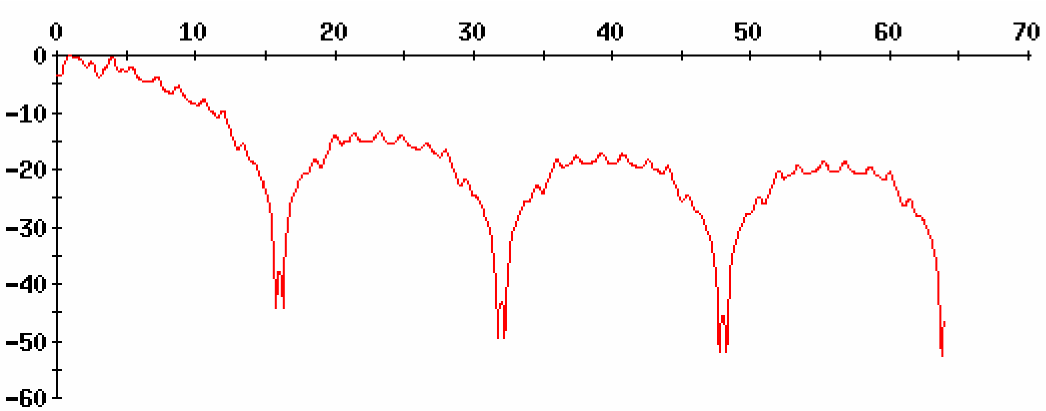


Figure 5 – The spectrum of the spread signal is as wide as the code sequence

The spectrum has spread from 2 Hz to 16 Hz, by a factor of 8. This number is called the the spreading factor or the processing gain (in dBs) of the system. This process can also be called a form of binary modulation. Both the Data signal and the modulating sequence in this case are binary signals.

If original signal is x(t) of power P_s, and the code sequence is given by g(t), the resultant modulated signal is

$$s(t) = \sqrt{2P_s}\,\underline{d(t)g(t)}$$

The multiplication of the data sequence with the spreading sequence is the first modulation. Then the signal is multiplied by the carrier which is the second modulation. The carrier here is analog.

$$s(t) = \sqrt{2P_s}\,\underline{\underline{d(t)g(t)}\sin(2\pi f_c t)}$$

On the receive side, we multiply this signal again with the carrier. What we get is this.

$$rcv(t) = \sqrt{2P_s}\,d(t)g(t)\sin^2(2\pi f_c t)$$

By the trigonometric identity

$$\sin^2(2\pi f_c t) = 1 - \underline{\cos(4\pi f_c t)}$$

we get

$$rcv(t) = \sqrt{2P_s}\,d(t)g(t)(1 - \underline{\cos(4\pi f_c t)})$$

Where the underlined part is the double frequency extraneous term, which we filter out and we are left with just the signal.

$$rcv(t) = \sqrt{2P_s}\,d(t)g(t)$$

Now we multiply this remaining signal with g(t), the code sequence and we get

$$rcv(t) = \sqrt{2P_s}\,d(t)g(t)g(t)$$

Now from having used a very special kind of sequence, we say that correlatation of g(t) with itself (only when perfectly aligned) is a certain scalar number which can be removed, and we get the original signal back.

$$rcv(t) = \sqrt{2P_s}\,d(t)$$

In CDMA we do modulation twice. First with a binary sequence g(t), the properties of which we will discuss below and then by a carrier. The binary sequence modulation ahead of the carrier modulation accomplishes two functions, 1. It spread the signal and 2. It introduces a form of encryption because the same sequence is needed at the receiver to demodulate the signal.

In IS-95 and CDMA 2000 we do this three times, once with a code called Walsh, then with a code called Short Code and then with one called Long code.

Properties of spreading codes

Multiplication with the code sequence which is of a higher bit rate, results in a much wider spectrum. The ratio of the code rate to the information bit rate is called both the **spreading factor** and the **processing gain** of the CDMA system. In IS-95, the chipping rate is 1.2288 and the spreading factor is 64. Processing gain is usually given in dBs.

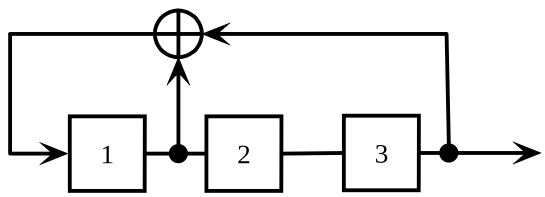
To distinguish the information bit rate from the code rate, we call the code rate, chipping rate. In effect, we take each data bit and convert it into k chips, which is the code sequence. We call it the chipping rate because the code sequence applied to each bit is as you can imagine it chipping the original bit into many smaller bits.

For CDMA spreading code, we need a random sequence that passes certain “quality” criterion for randomness. These criterion are

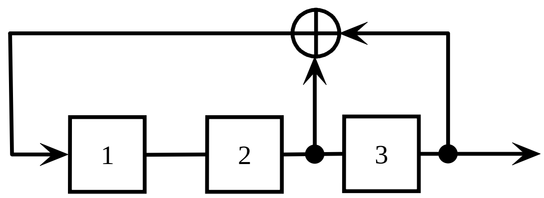
1. The number of runs of 0’s and 1’s is equal. We want equal number of two 0’s and 1’s, a length of three 0’s and 1’s and four 0’s and 1’s etc. This property gives us a perfectly random sequence.
2. There are equal number of runs of 0’s and 1’s. This ensures that the sequence is balanced.
3. The periodic autocorrelation function (ACF) is nearly two valued with peaks at 0 shift and is zero elsewhere. This allows us to encrypt the signal effectively and using the ACF peak to demodulate quicklt.

Binary sequences that can meet these properties are called **optimal binary sequences**, or **pseudo-random sequences**. There are many classes of sequences that mostly meet these requirements, with m-sequences the only ones that meet all three requirements strictly. These sequences can be created using a shift-registers with feedback-taps. By using a single shift-register, **maximum length sequences** can be created and called often by their shorter name of **m-sequence**, where m stands for maximum.

m-sequences and the Linear Feed Shift-Register



3 stage LFSR generating m-sequence of period 7., using taps 1 and 3.



Another 3 stage LFSR generating m-sequence of period 7, using taps 2 and 3

Figure 6 – The structure of linear feedback registers (LFSR) from which m-sequences can be created

m–sequences are created using **linear feedback registers (LFSR)**. Figure 6 shows a three register LFSR with two different tap connection arrangements. The tap connections are based on primitive polynomials on the order of the number of registers and unless the polynomial is irreducible, the sequence will not be a m-sequence and will not have the desired properties.

Each configuration of N registers produces one sequence of length 2^N. If taps are changed, a new sequence is produced of the same length. There are only a limited number of m-sequences of a particular size.

The cross correlation between an m-sequences and noise is low which is very useful in filtering out noise at the receiver. The cross correlation between any two different m-sequences is also low and is useful in providing both encryption and spreading. The low amount of cross-correlation is used by the receiver to discriminate among user signals generated by different m-sequences.

Think of m-sequence as a code applied to each message. Each letter (bit) of the message is changed by the code sequence. The spreading quality of the sequence is an added dimensionality and benefit in CDMA systems.

Gold sequences

Combining two m-sequences creates **Gold codes**. These codes are used in asynchronous CDMA systems.

Gold sequences are an important class of sequences that allow construction of long sequences with three valued Auto Correlation Function ACFs. Gold sequences are constructed from pairs of preferred m-sequences by modulo-2 addition of two maximal sequences of the same length.

Gold sequences are in useful in non-orthogonal CDMA. (CDMA 2000 is mostly an orthogonal CDMA system) Gold sequences have only three cross-correlation peaks, which tend to get less important as the length of the code increases. They also have a single auto-correlation peak at zero, just like ordinary PN sequences.

The use of Gold sequences permits the transmission to be asynchronous. The receiver can synchronize using the auto-correlation property of the Gold sequence.

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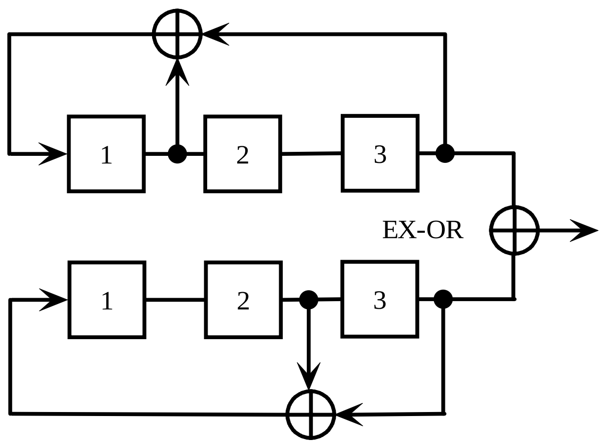

Figure 7 – Generating Gold codes by combining two preferred pairs of m-sequences

More codes

IS-95 and IS-2000 use two particular codes that are really m-sequences but have special names and uses. These are called **long codes** and **short codes**.

Long code

The Long Codes are 2^{42} bits (created from a LFSR of 42 registers) long and run at 1.2288 Mb/s. The time it takes to recycle this length of code at this speed is 41.2 days. It is used to both spread the signal and to encrypt it. A cyclically shifted version of the long code is generated by the cell phone during call setup. The shift is called the **Long Code Mask** and is unique to each phone call. CDMA networks have a security protocol called CAVE that requires a 64-bit authentication key, called A-key and the unique ESN (Electronic Serial Number, assigned to mobile based on the phone number). The network uses both of these to create a random number that is then used to create a mask for the long code used to encrypt and spread each phone call. This number, the long code mask is not fixed but changes each time a connection is created.

There is a Public long code and a Private long code. The Public long code is used by the mobile to communicate with the base during the call setup phase. The private long code is one generated for each call then abandoned after the call is completed.

Short code

The short code used in CDMA system is based on a m-sequence (created from a LFSR of 15 registers) of length $2^{15} - 1 = 32{,}767$ codes. These codes are used for synchronization in the forward and reverse links and for cell/base station identification in the forward link

The short code repeats every 26.666 milliseconds. The sequences repeat exactly 75 times in every 2 seconds. We want this sequence to be fairly short because during call setup, the mobile is looking for a short code and needs to be able find it fairly quickly. Two seconds is the maximum time that a mobile will need to find a base station, if one is present because in 2 seconds the mobile has checked each of the allowed base stations in its database against the network signal it is receiving.

Each base station is assigned one of these codes. Since short code is only one sequence, how do we assign it to all the stations? We cyclically shift it. Each station gets the same sequence but it is shifted.

From properties of the m-sequences, the shifted version of a m-sequences has a very small cross correlation and so each shifted code is an independent code. For CDMA this shift is 512 chips for each adjacent station. Different cells and cell sectors all use the same short code, but use different **phases or shifts**, which is how the mobile differentiates one base station from another. The phase shift is known as the **PN Offset**. The moment when the Short code wraps around and begins again is called a **PN Roll**. If I call the word "please" a short code, then I can assign, "leasep" to one user, "easepl" to another and so on. The shift by one letter would be my PN Offset. So if I say your ID is 3, then you would use the code "aseple".

A mobile is assigned a short code PN offset by the base station to which it is transmitting. The mobile adds the short code at the specified PN offset to its traffic message, so that the base station in the region knows that the particular message is meant for it and not to the adjacent base station. This is essentially the way the primary base station is identified in a phone call. The base station maintains a list of nearby base stations and during handoff, the mobile is notified of the change in the short code.

There are actually two short codes per base station. One for each I and Q channels to be used in the quadrature spreading and despreading of CDMA signals.

Walsh codes

In addition to the above two codes, another special code, called Walsh is also used in CDMA. Walsh codes do not have the properties of m-sequences regarding cross correlation.. IS-95 uses 64 Walsh codes and these allow the creation of 64 channels from the base station. In other words, a base station can talk to a maximum of 64 (this number is actually only 54 because some codes are used for pilot and synch channels) mobiles at the same time. CDMA 2000 used 256 of these codes.

Walsh codes are created out of **Haddamard** matrices and Transform. Haddamard is the matrix type from which Walsh created these codes. Walsh codes have just one outstanding quality. In a family of Walsh codes, all codes are orthogonal to each other and are used to create channelization within the 1.25 MHz band.

Here are first four Hadamard matrices. The code length is the size of the matrix. Each row is one Walsh code of size N. The first matrix gives us two codes; 00, 01. The second matrix gives: 0000, 0101, 0011, 0110 and so on.

$$H1 = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

$$H2 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

$$H3 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{pmatrix}$$

In general each higher level of Hadamard matrix is generated from the previous by the **Hadamard transform**

$$H_{N+1} = \begin{pmatrix} H_N & H_N \\ H_N & \overline{H_N} \end{pmatrix}$$

Where $\overline{H_N}$ is the inverse of H_N.

Their main purpose of Walsh codes in CDMA is to provide orthogonality among all the users in a cell. Each user traffic channel is assigned a different Walsh code by the base station. IS-95 has capability to use 64 codes, whereas CDMA 2000 can use up to 256 such codes. Walsh code 0 (which is itself all 0s) is reserved for pilot channels, 1 to 7 for synch and paging channels and rest for traffic channels. They are also used to create an orthogonal modulation on the forward link and are used for modulation and spreading on the reverse channel.

Orthogonal means that cross correlation between Walsh codes is zero when aligned. However, the auto-correlation of Walsh-Hadamard codewords does not have good characteristics. It can have more than one peak and this makes it difficult for the receiver to detect the beginning of the codeword without an external synchronization. The partial sequence cross correlation can also be non-zero and un-synchronized users can interfere with each other particularly as the multipath environment will differentially delay the sequences. This is why Walsh-Hadamard codes are only used in synchronous CDMA and only by the base station which can maintain orthogonality between signals for its users.

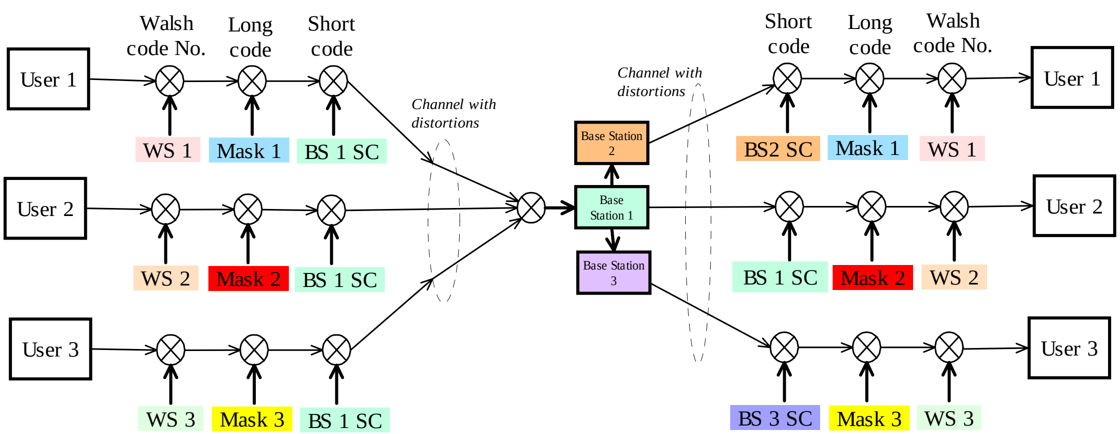

Figure 8 – Relationship codes used in CDMA

The above is simplified look at the use of these codes. Assume there are three users in one cell. Each is trying to talk to someone else. User 1 wants to talk to someone who is outside its cell and is in cell 2. User 3 wants to talk to someone in cell 3.

Let's take User 1. Its data is first covered by a channel Wash code, which is any Walsh code from 8 to 63. It is assigned to the user by the base station 1 in whose cell the mobile is located. The Base Station has also assigned different Walsh codes to users 2 and 3. All three of these are different are assigned by base station 1 and are orthogonal to each other. This keeps the data apart at the base station. Now based on the random number assigned by the BS, the mobile generates a long code mask (which is just the starting point of the long code sequence and is a scalar number). It now multiplies the signal by this long code starting at the mask ID. Now it multiplies it by the short code of the base station to whom it is directing the signal.

When the base station receives this signal, it can read the long code and see that the message needs to be routed to base station 2. So it strips off 1st short code and adds on the short code of base station 2 which is then broadcast by the BS 1 to BS 2 or sent by landlines. BS2 then broadcasts this signal along to all mobiles in its cell. The users who is located in this cell, now does the reverse. It multiplies the signal by the BS 2 short code (it knows nothing about BS 1 where the message generated) then it multiplies the signal by the same long code as the generating mobile. How? During the call paging, the mobile was given the same random number from which it creates the same long code mask. After that it multiplies it by the Walsh code sequence (also relayed during call setup).

So that's about it with some additional bells and whistles, which we shall get to shortly.

Channel waveform properties

The communications between the mobile and the base station takes place using specific channels. Figure below shows the architecture of these channels.

The forward channel (from base station to mobile) is made up of the following channels:

Pilot channel (always uses Walsh code W0) (Beacon Signals)
Paging channel(s) (use Walsh codes W1-W7)
Sync channel (always uses Walsh code W32)
Traffic channels (use Walsh codes W8-W31 and W33-W63)

The reverse channel (from mobile to base station) is made up of the following channels:

Access channel
Traffic channel

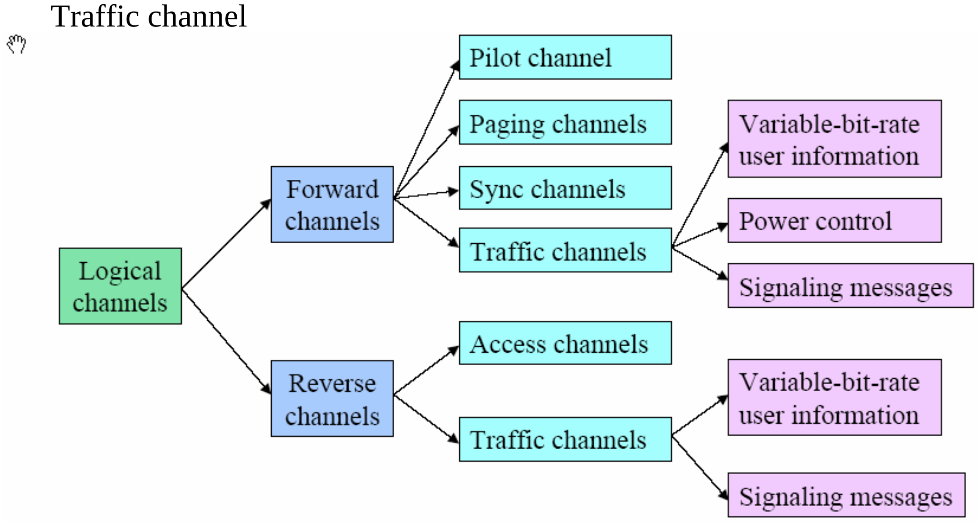

Figure 9 – Forward channel

Forward Channel description

A base station can communicate on up to 64 channels. It has one pilot signal, one synch channel and 8 paging channels. The remaining are used for traffic with individual mobiles.

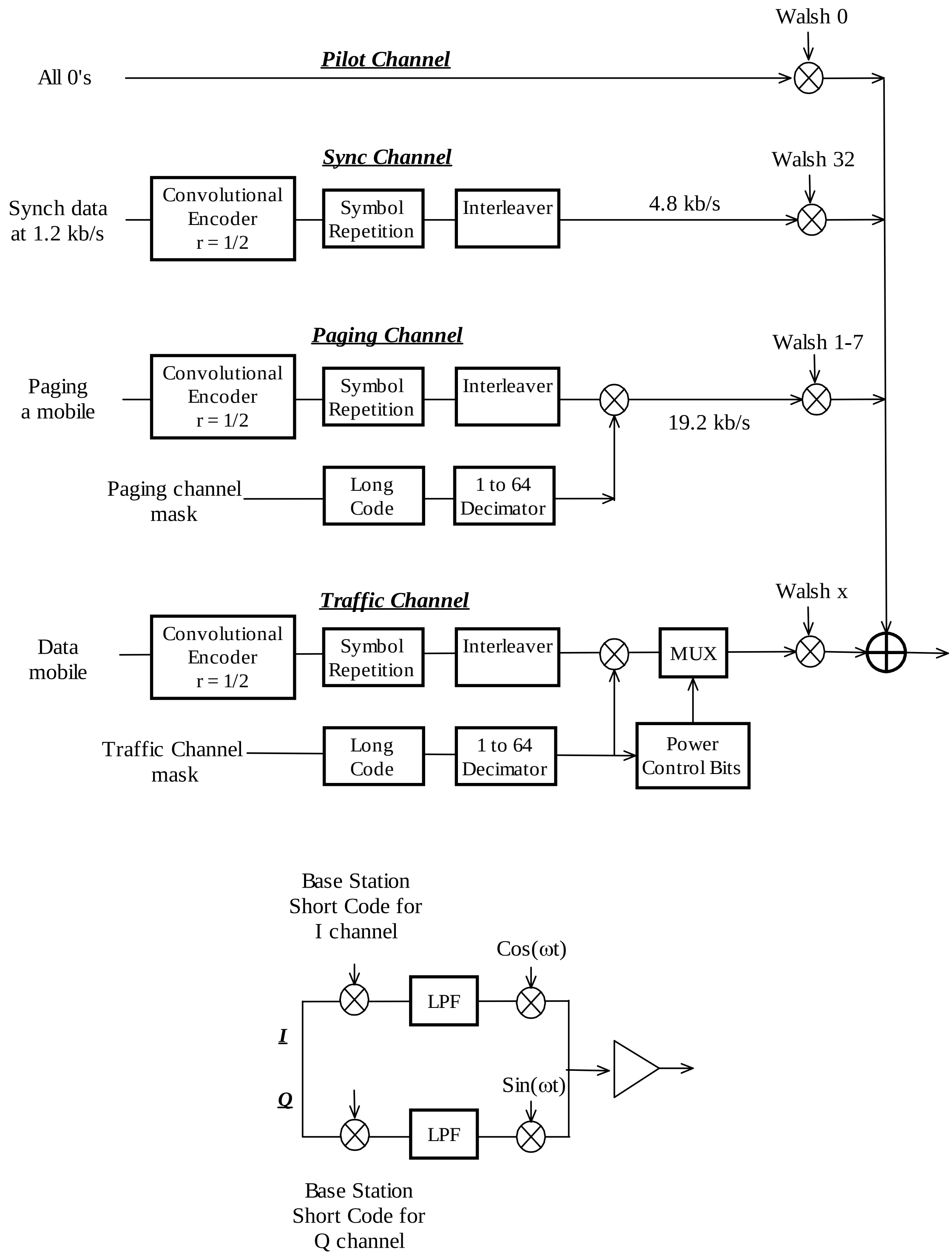

Figure 10 – Forward channel is the transmission of all traffic from the base station within its cell. All data is sent simultaneously.

Pilot Channel

Let's start with how the base station establishes contact with the mobiles within its cell. It is continually transmitting an all zero signal, which is covered by a Walsh code 0, a all 0's code. So what we have here is a one very long bit of all zeros. For this reason, the pilot channel has very good SNR making it easy for mobiles to find it. This all zero signal is then multiplied by the base stations' short code, which if you recall is the same short code that all base station use, but each with different PN offset. Pilot PN Offsets are always assigned to stations in multiples of 64 chips, giving a total of 512 possible assignments. The 9-bit number that identifies the pilot phase assignment is called the **Pilot Offset.**

This signal is real so it only goes out on the I channel, and is up-converted to the carrier frequency which in the US is 845 MHz.

On the receive side, the mobile picks up this signal and notes the base station that is transmitting it. Here is a question, if the short code is cyclical, how does the receiver know what the phase offset is. Do not all the signals from all the other nearby base stations look the same? Yes, and the mobile at this point does not know which base station it is talking to, only that it has found the network. To determine of all the possible base station and there can 256 of them, each using a 512 chip shifted short code, the network uses the GPS signal and timing.

The zero offset base station aligns its pilot transmission with every even second time tick of GPS. So let's say that your mobile is in the cell belonging to a base station with PN offset ID of 10. That means that is will start its transmission 10 x 512 chip = 5120 chips after every even second time tick. So when the mobile wakes up and looks at it time, it knows exactly where each base station short code should be. Then all it has to do is to do a correlation of the bits it is seeing with each of the 256 possible sequences. Of course, it tries the base station where it was last but if it has been moved then theoretical it will have to go through all 256 correlations to figure out where it is. But it does do it and at the end of the process, it knows exactly which of the base stations it is hearing.

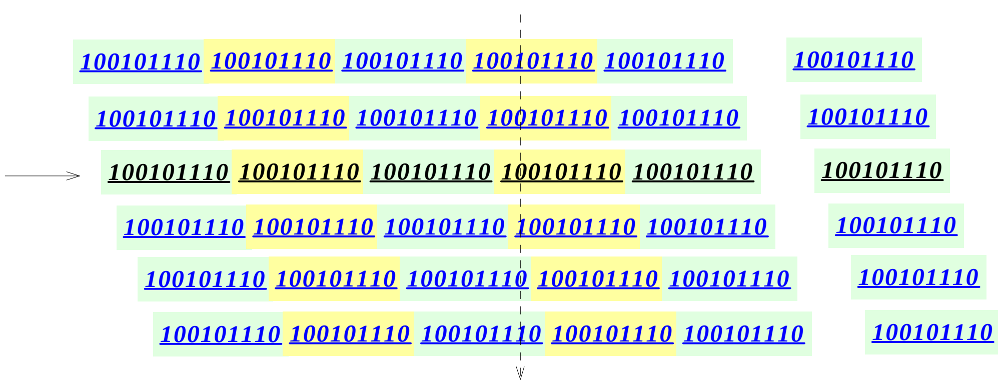

Figure 11 – The mobile looks for the code that aligns with GPS timing. It picks off the code received at this time, does a correlation with stored data and knows which base station it has found.

Synch Channel

The Synch channel information includes the pilot offset of the pilot the mobile has acquired. This information allows the mobile to know where to search for the pilots in the neighbor list. It also includes system time, the time of day, based on Global Positioning Satellite (GPS) time. The system time is used to synchronize system functions. For instance, the PN generators on the reverse link use zero offset relative to the even numbered seconds in GPS time. However, the mobiles only know system time at the base stations plus an uncertainty due to the propagation delay from its base station to the mobile's location. The state of the long code generator at system time is also sent to the mobile in the Synchronization message. This allows the mobile to initialize and run its long code generator very closely in time synchronism with the long code generators in the base stations. The Synchronization message also notifies the mobile of the paging channel data rate, which may be either 4800 or 9600 bits/sec. The data rate of this channel is always 1200 bps.

Paging Channel

Now the mobile flashes the name of the network on its screen and is ready to receive and make calls. Your paging channel may now be full of data. It may include a ring tone or a “voicemail received” message. The data on the paging channel sent by the base station, includes mobile **Electronic Serial Identification Number (ESIN)**, and is covered by a long code. How does the mobile figure out what this long code is? At the paging level, the system uses a public long code. This is because it is not talking to a specific mobile, it is paging and needs to reach all mobiles. When the correct mobile responds, a new private long code will be assigned at that time before the call will be connected. The mobile while scanning the paging channel recognizes its phone number and responds by ringing. When you pick up the call, an access message goes back to the base station.

The mobile using Qualcomm CDMA generatse a 18-bit code. The mobile sends this authentication sequence to the base station during the sync part of the messaging protocol. The base station checks the authentication code before allowing call setup. It then issues a random number to the mobile, which the mobile uses in the CAVE algorithm to generate a call specific long code mask. At the same time, the base station, will also do exactly that. The two now have the same long code with which to cover the messages.

Traffic Channel

The base station can transmit traffic data to as many as 54 mobiles at the same time. It keeps these channel separate by using Walsh codes. This is a code division multiplexing rather than a frequency based channelization. Walsh codes are used only by the base station and in this fashion, it is a **synchronous CDMA** on the forward link, whereas on the return link it is **asynchronous CDMA**, because there is no attempted separation between the various users. But the use of m-sequences for spreading, the quality of orthogonality although not perfect is very very good.

The traffic channel construct starts with baseband data at 4.8 kbps. It is then convolutionally encoded at rate of ½, so the data rate now doubles to 9.6 kbps. Symbol repetition is used to get the data rate up to 19.2 kbps. All information rates are sub-multiples of this rate. Data is then interleaved. The interleaving does not change the data rate, only that the bits are reordered to provide protection against burst errors. Now at this point, we multiply the resulting data sequences with the long code, which starts at the point determined by the private random number generated by both the base station and the mobile jointly. This start point is call-based and changes every time. Mobiles do not have a fixed long code assigned to them. Reverse CDMA Channel can have up to 2^{42}-1 logical channels or the total number of calls that can be served are 17179869184.

Now the data is multiplied by a specific Walsh codes which is the nth call that the base station is involved in. Mobile already knows this number from the paging channel.

The base station then combines all its traffic channels (each covered by a different Walsh code) and all paging channels (just 8) and the one pilot channel and one synch channel adds them up, does serial to parallel conversion to I and Q channels. Each is then covered by a I and a Q short code and is QPSK modulated up to carrier frequencies and then transmitted in the cell.

Reverse Channels

In IS-95, there are just two channels on which the mobile transmits, and even that never simultaneously. It is either on the access channel or it is transmitting traffic. The channel structure is similar but simpler to the forward channel, with the addition of 64-ary modulation.

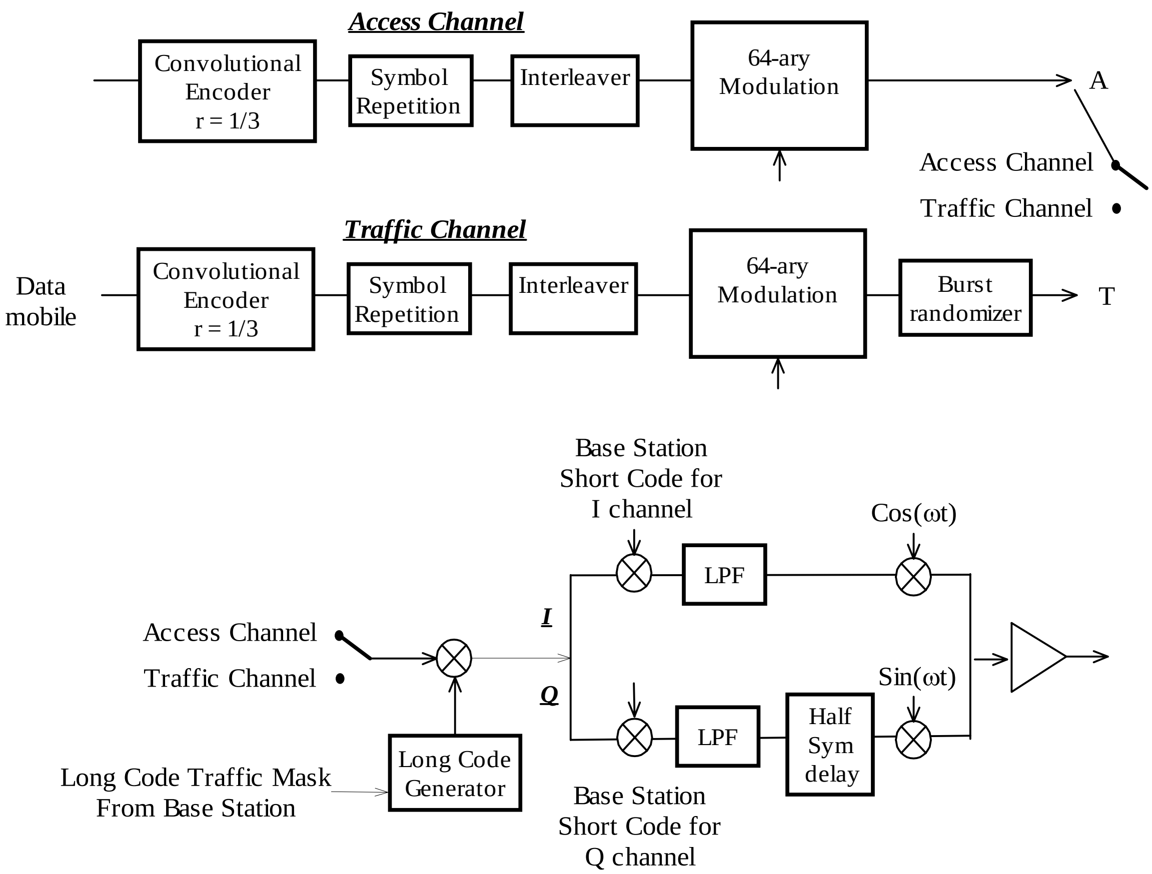

Figure 12 – Reverse Channel - from mobile to base station communication

64-ary modulation

This block takes a group of six incoming bits (which makes $2^6 = 64$ different bit sequences of 6 bits) and assigns a particular Walsh code to each. We know that each Walsh code sequence is orthogonal to all the others so in this way, a form of spreading has been forced on the arbitrarily created symbols of 6 bits. And this spreading also forces the symbols to be orthogonal. It is not really a modulation but is more of a spreading function because we still have not up converted this signal to the carrier frequency. After this, a randomization function is employed to make sure we do not get too many 0's or 1's in a row. This is because certain Walsh codes have a lot of consecutive 0's.

Next comes multiplication with the long code starting at a particular private start point. Then comes serial to parallel conversion, and application of baseband filtering which can be a Gaussian or a root cosine shaping.

Then the Q channel (or I, it makes no difference) is delayed by half a symbol, as shown below. The reason this is done is to turn this into an offset QPSK modulated signal. The offset modulated signal has a lower non-linearity susceptibility and is better suitable to being transmitted by a class C amplifier such as may be used in a CDMA cell phone.

From there, each I and Q channel is multiplied by the rf carrier, (a sine and a cosine of frequency f_c) and off the signal goes to the base station.

On the demodulation side, the most notable item is the Rake receiver. Due to the presence of multipath, Rake receivers which allow maximal combining of delayed and attenuated signal, make the whole thing work within reasonable power requirements. Without Rake receivers, your cell phone would not be as small as it is.

Power control

Assume that there is only one user of the system. The carrier power

$C = SNR = E_b/T_b = R\ E_b$

If we define the transmit power equal to W and signal bandwidth equal to B, then the Interference power at the receiver is equal to

$I = W\ N_0$

Now we can write

$$\frac{C}{I} = \frac{R\ E_b}{W\ N_0} = \frac{E_b / N_0}{W / R}$$

The quantity W/R is the processing gain of the system. Now let's call M the number of users in this system. The total interference power is equal to

$$I = C\ (M - 1)$$

Substituting this in the above equation, we get,

$$\frac{C}{I} = \frac{C}{C(M-1)} = \frac{1}{M-1}$$

and with one more substitution we get

$$\frac{C}{I} = \frac{E_b / N_0}{W / R} = \frac{1}{M-1}$$

$$M \approx M - 1 = \frac{W}{R} \frac{1}{E_b / N_0}$$

So we conclude that the system capacity is a direct function of the processing gain for a given Eb/N0. What you may not have noticed is that we made an assumption that all users have similar power level so the interferences are additive. No one user overwhelms all the others. If the power levels of all users are not equal then the system capacity is compromised and the C/I expression above is not valid.

The CDMA systems manage the power levels of all mobiles so that the power level of each mobile is below a certain required level and is about the same whether the mobile is very close to the base station or far at the edge of the cell. Multipath and fading also attenuate power levels so the system maintains a power control loop.

IS-95 has a open-loop and a closed loop power management system. The open loop is a quicker way to manage power levels. The forward and reverse links are at different frequencies so they fade differently and open loop power control allows the mobile to adjust its power without consulting with the base station. In closed loop power control the base station measures the power level of the access channel signal sent by the mobile and then commands with 1 in the synch channel if the power needs to be raised and with 0 if it is to be reduced by 1 dB at a time. The closed loop power control also uses an outer loop power control. This method measures the **Frame Error Rate (FER)** both by the mobile and the base station and then adjusts the power according to whether the FER is acceptable.

CDMA 2000

This is an evolution and extension of capabilities and builds on the IS-95 standard. One of the big ways in which CDMA 2000 differs from IS-95 is that it includes beam forming. Each base station cell is now divided in three sectors such that frequency is reused. This increases the gain at the mobile and allows better SNR and a larger number of users. The other significant way that IS-2000 differs from IS-95 is that it allows additional forward and reverse channels. Some of these channels are the same as IS-95 and others are new. Spreading codes are also changed to allow larger data rates. The 1.25 MHz channel with the 1.2288 mbps spreading rate called 1X can now be 3X 93 x 1.2288 mbs) or 5X (5 x 1.2288 mbps)

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