# Adding Direct Sequence Spread Spectrum to a Continuous Wave RF Ranging System

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*By*

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# Abstract

Continuous wave ranging systems have an inherent problem of range ambiguity. Direct sequence spread spectrum is added to an existing commercial CW ranging system to eliminate the ambiguity and to capitalize on the other advantages that spread spectrum offers. These include increased process gain and multipath rejection.

The proposal investigates the different functions required to modify the existing continuous wave system. Circuits and components are designed and analyzed to implement the specific functions. All the digital components are modeled and simulated on a Field Programmable Gate Array. The analog components are evaluated through experiments and the results are presented. From the results of the simulations and analyses, it is concluded that the implementation of the proposal is both feasible and practical.

# Acknowledgments

I would like to express my sincere gratitude to my advisor Dr. Ron J. Palmer. His continual support and guidance in the area of navigation and positioning were instrumental in the completion of my research and thesis work. I would also like to thank Accutrak Systems Ltd. for providing me with the support to make this research possible.

I would like to thank the Faculty of Engineering and the department of Graduate Studies for the opportunity and support to make this research work possible.

## Dedicated to

*My Late mother, Ramila H. Patel,*

*My wife and sons, Anagha, Rushi and Kunal.*

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## Chapter One

# 1. INTRODUCTION

Technological advances in almost every field came about due to the need to achieve more capabilities than what were currently available. These advances established newer and increased capacities, which led to a further need for technological advancements. These development cycles of various technologies led to today's modern world of sophistication and technological advances to perform various tasks more efficiently. Figure 1.1 shows a typical development cycle.

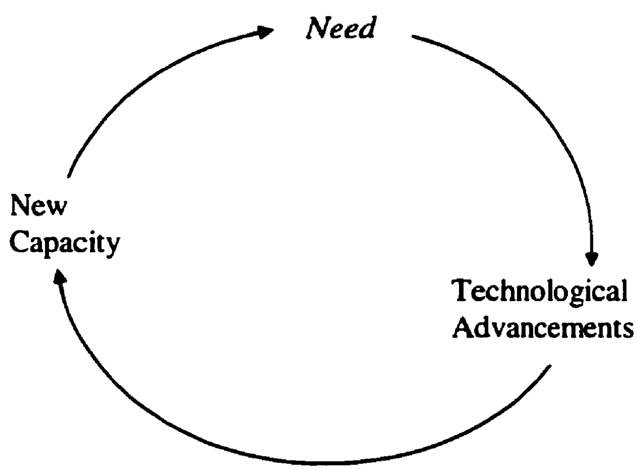



Figure 1.1 Development Cycle

One such development cycle was that of navigation. It has led to various techniques and methods to achieve new capacities, which have led to more needs that required more precision and reliable positioning. This thesis addresses this need and a new technique is proposed which is based upon combining two existing techniques, to satisfy the newer needs for more accuracy and reliability in positioning.

## *1.1 Development of Navigation Techniques*

In early medieval times, European people were relatively stationary; the need for traveling large distances from home was not necessary. As trade grew and the exchange of goods with other settlements became more common, people traveled farther distances from their homes, from which the need for position location (the knowledge of present location with reference to a known location) originated. The knowledge of landmarks and coastal features was used to establish position location during early land and coastal trading missions. As trade routes became more extensive, this technique was enhanced by creating man-made landmarks to guide other traders and travelers to distant locations. At first, directions for the use of these landmarks were passed on orally from master to apprentice. Record keeping of these directions was the next step towards navigating efficiently.

As voyagers ventured across the ocean, the use of landmarks became less practicable and the need for better techniques developed. The magnetic compass, introduced in the 12th century, was the main navigational aid to Mediterranean sailors. This led to the technique of dead-reckoning, derived from the term deduced reckoning, which used the ship's course and speed to estimate current position. Estimation was not sufficiently accurate for long voyages, which led to navigation through the observation of heavenly bodies, particularly the sun, the moon and the pole star. Techniques of celestial navigation enabled 15th century Portuguese sailors to sail beyond Mediterranean waters.

These were the early days of the "Age of Discovery" where sailors carried out methodical exploration of the Atlantic. During this era, the technique of finding latitude and longitude from astronomical observations was established. When out of the sight of land, sailors could determine a ship's position with increased reliability. These techniques became the basis of modern navigation.

The need for determining exact position led to other methods and development of new tools and devices. The sextant and Jacob's staff had calibrated scales and a sight which were used to line up the heavenly body and the horizon, giving the longitude and latitude of the current location. In the mid 1700s the first official British nautical almanac was published to help sailors determine longitude from lunar observations. At about the same time, accurate time keeping devices such as the chronometer aided mariners by providing reliable and accurate ascertainment of latitude and longitude. [1]

In the early 1800s the concept of "Line of Position" was discovered, which was basically a line indicating a series of possible positions of a craft, usually determined by observation [2]. The point intersection of two such lines of position gave the position of the craft, also known as a "<u>fix</u>". This technique of position fixing is the basis of today's modern navigation and position location, the only difference being in the methods of obtaining the lines of position and the accuracy obtained. The need for more accurate and faster readings led to more technological advancements. Devices such as the gyrocompass and sonic depth sounders were used in addition to the existing techniques for position location.

In the early 20th century, the first radio aid to navigation was invented. A radio transmitted a time signal, which was used to determine longitude, in effect replacing the chronometer. Later on with more advancements in technology the ship's bearings could be determined from three land based radio transmitters using the line of position technique. Radio techniques had the definite advantage over the other observation methods of not being affected by weather conditions such as fog or cloudiness.

During World War I and after, technological advances in the field of radio navigational techniques and electronics took place rapidly to respond to more stringent navigational needs for flying machines. Even faster position location was required during World War II. The problem of enemy detection led to the invention of RADAR (radio detection and ranging), using high frequency radio energy. The RADAR system illuminates the air space with radio waves, and when a target such as an aircraft enters this air space, it scatters part of the radio energy. This small scattering is picked up by the receiver, whereupon amplification shows the presence of the aircraft. To enhance this capability, different modifications were made to determine the range and bearing of the aircraft. In the 1940s and 1950s the technique of hyperbolic navigation came into use. This method involves lines of position in the form of hyperbolas, based upon accurate measurement of the difference in time taken by radio signals from two fixed transmitters to reach the receiver. This hyperbolic technique led to systems like LORAN (LOng RAnge Navigation), OMEGA and even to the present day technology of GPS (Global Positioning System).

The applications of navigation that were developed mainly for military exigencies have now been extended to many civilian uses such as sports and mining. The application most closely linked to early navigation is surveying. The accuracy needed for surveying and other commercial applications led to further advancements in technology; to obtain accurate position location more accurate range measurement techniques were developed. Accurate positioning is needed mostly in applications like precision farming, mine sweeping, driverless vehicles, etc. In farming, where repetitive work is involved and utilization of expensive chemicals are used to improve yield, precisely guiding the operator to avoid waste of time and chemicals is necessary. In mine sweeping mapping and locating the explosive charge on a field and safe detonation or defusing requires high accuracy. Navigating a driverless vehicle to perform repetitious or dangerous tasks also requires high accuracy.

This thesis will investigate two modern radio range measurement techniques that provides accurate positioning and proposes one hybrid technique to overcome the shortcomings of each technique. Before a detailed analysis of the two range measurement techniques can be undertaken however, a brief description of other ranging techniques must be given and the terminology used in conjunction with these techniques defined.

## 1.2 Range Measurement

The basic principle of most current range measurement techniques is the measurement of propagation delay of a periodic wave. SONAR ranging, infrared ranging and radio frequency ranging are the three most commonly used range measurement techniques today. Depending on the frequency of the periodic waves used, these techniques are best suited for certain applications.

**SONAR range measurement**: The SONAR (an acronym for SOund NAvigation and Ranging) method is based on the reflection of underwater sound waves traveling at the rate of 1,500 meter/sec (5,000 feet/sec). A typical SONAR system emits an ultrasonic wave at a frequency range anywhere from above 20 kHz to 1 GHz (audible sound waves extend from 30 to 20,000 Hz). The attenuation of sound waves increases with the frequency used; higher frequency waves attenuate more. The sound waves are subject to refraction, reflection and scattering upon interception of a solid object.

A SONAR system transmits a short pulse of sound energy using an underwater hydrophone; the time taken by the waves reflected by a target to reach the transmitter indicates the position of the target. The applications of this method mainly lie in underwater detection and location of objects by acoustical echo. The extent and effectiveness of SONAR can be affected by turbulence in the water, unwanted reflection by the surface and sound interference from aquatic animals (dolphins and whales).

**Infrared laser range measurement:** Emission of energy as electromagnetic waves in the portion of the spectrum just beyond the limit of the red portion of visible radiation is known as infrared radiation. The speed of infrared waves traveling through air is the same as that of the speed of light ($3 \times 10^8$ m/s). The infrared laser (light amplification by stimulated emission of radiation) is generated by focusing a high intensity beam of infrared light. To measure distance, this beam of infrared laser is transmitted and reflected from a highly reflective and focused prism arrangement. The amount of time required for the light to return to the transmitter would indicate the distance of the reflector from the transmitter.

This technique normally yields a very accurate distance measurement, usually in the order of magnitude of centimeters. Due to the highly accurate measurement capability, the main application of infrared ranging has been in the field of commercial surveying. The main limitation of this technique is that line of sight is required and that, distortion or attenuation of the reflected wave due to any atmospheric condition leads to errors. Presence of heat waves rising from the ground or dust clouds may also result in reduced accuracy or inoperability.

**RF (Radio frequency) range measurement**: All RF signals travel at the speed of light and are subject to effects of reflection, refraction and scattering. RF waves extend from 3 kHz to 1000 GHz and have different characteristics that are related to the frequency. Different navigational applications have utilized these differences. All radio frequency signals are subject to a fixed rate of propagation, approximately 3.7 μsec/km (6 μsec/mile) in air. Measurement of propagation delay from a transmitter to a receiver indicates the distance between the transmitter and the receiver. Because signaling waveforms and modulation are also functions of time, the difference in a signaling waveform seen at the receiver from that present at the transmitter can also be directly related and used to measure distance. The advantage of using any kind of radio frequency is that atmospheric factors do not affect the capability of measuring position. The limitations of any RF position measurement system are interference from unwanted reflection, constructive and destructive addition of reflection from the ionosphere and ground ( known as multipath ), or reception from other transmitting sources. Obstacles can cause the RF system to become inoperable or lead to erroneous position measurement.

RF ranging techniques are currently the most common method used by systems to yield positioning information. A brief investigation of the most commonly used RF ranging applications will illustrate their particular characteristics.

## 1.3 Types of RF Ranging

The different methods used to measure propagation delay of a periodic wave through air result in systems or techniques with different limitations and advantages. The following sections describe briefly the principle and the capacity of some common RF ranging techniques.

### 1.3.1 RADAR

This is one of the most commonly known applications of radio frequency ranging. This method was originally developed for military applications. The property of RF waves reflecting from conductive surfaces is utilized. A highly directional antenna is used to transmit a pulse of RF wave towards a conductive target. The time required for the reflection caused by the target to reach back to the antenna is then measured. This measured time is a representation of the distance of the target from the antenna. The target is not aware of its detection and no special hardware is required at the target (passive system). This technique is particularly useful for military applications. However, the accuracy of the received reading is normally in the order of tens of meters. Accuracy is limited by the ability of the system to accurately measure the time difference between transmission and reception of a RADAR pulse. A further limitation to this system is the inability to distinguish signals that are reflected by other objects.

### 1.3.2 Multiple frequency / Tone ranging

This technique uses multiple coherent tones that modulate a carrier. All tones are started from the same phase. At a point distant from the point of origin, all the tones have a unique phase relationship with respect to each other. This information reduces the ambiguity. Ambiguity is a problem with single frequency continuous wave systems in which the integer number of cycles is unknown. The resolution of measuring range at the receiver depends on the ability to measure the phase of the highest tone. This technique is limited by the ability to produce coherent tones.

### 1.3.3 CW (Continuous Wave) ranging

In this technique a carrier is transmitted with a known phase, and the phase of the reflection received from a stationary reflective transponder is measured. The phase difference is proportional to the distance traveled by the carrier from the transmitter to the transponder and back. The phase difference from one transmitter and one reflector results in a hyperbolic line of positions. Intersection of more than one such hyperbola provides the position of the receiver with respect to the position of the transmitter and the reflector. Very fine accuracy can be achieved if an accurate phase measurement technique is available. A CW system has been developed using accurate phase measurement to achieve position measurement accuracy to within ± 15 cm [14]. This accuracy is obtained by measuring the phase using digital techniques, and compensating for various delays within the system[15].

This CW method has a limitation of not being able to resolve the measured range over more than one wavelength unless initialization and cycle tracking are used. Another weakness of the technique is due to the operation on a single frequency multipath and fading can render the system inoperable in certain areas.

### 1.3.4 Spread spectrum ranging

Spread spectrum techniques were initially developed by the military to send data and messages without being affected by jamming (intentional interference) or detection by the enemy. This is done by transmitting the information on a much larger bandwidth than is necessary. This is called spreading. A pseudo-random (noise like) pattern known to both the transmitter and the receiver is transmitted and upon reception the same pattern is used to collapse the spread signal. Since the carrier energy is spread over a wide spectrum the effects of multipath and fading are minimal for a spread spectrum system as compared to a CW system.

Spread spectrum systems have applications in advanced communication as well as for position location. The spread spectrum technique is utilized in today's GPS, which was developed for military applications to guide missiles and aircraft during tactical operations, there are three different types of spread spectrum systems : chirp, direct sequence and frequency hopping.

Pulsed FM (frequency modulation) systems or chirp spread spectrum does not strictly employ any coding as in other spread spectrum techniques. The wide transmit bandwidth is achieved by transmitting a pulse of constant amplitude and duration. This frequency transmitted in this duration is linearly increased or decreased. This varying frequency pulse is known as a chirp signal. The main application of this technique was to improve the performance of the RADAR by achieving transmit power reduction.[13]

Direct sequence spread spectrum systems use a binary code to modulate the carrier to achieve a wider bandwidth. The propagation delay of the code, as seen at the receiver, is measured to determine a position. The code cycle and rate determines the performance of a direct sequence spread spectrum system. The basic resolution of ranging is proportional to the bit rate of the binary code.

In frequency hopping spread spectrum systems a binary code shifts the carrier frequency in a discrete pattern. The code rate employed in these systems is far lower than that of direct sequence spread spectrum systems. Although ranging can be achieved just as in direct sequence systems, position resolution is poorer because of the lower code rates. This technique is mainly used for securely transmitting voice and data.

## *1.4 Thesis proposal*

This thesis investigates currently used RF range measurement techniques for land based navigation, specifically for accurate mapping ( within 0.5 meter accuracy ) and guiding autonomous vehicles. Two RF systems are examined, one which uses the continuous wave technique and one which is based upon a spread spectrum technique. The continuous wave technique is more vulnerable to multipath and interference ( intentional or unintentional ) but capable of measuring accurate distance within one carrier cycle. It also requires initialization and carrier tracking to overcome the cycle ambiguity problem. The spread spectrum technique, on the other hand, has good rejection for multipath and interference and also can resolve range measurements over large distances without any ambiguity. It also provides the capability of achieving process gain which enables the system to operate in noisy conditions. However the position resolution of a spread spectrum system is limited by the bit rate of the code used ( chip rate ).

The continuous wave positioning technique though very accurate is still ambiguous and has limited operability in presence of interference. The spread spectrum positioning technique is not as accurate as the continuous wave technique but has no ambiguity problems for a large distances and has excellent immunity to interference. It would be desirable to develop a system that incorporates the advantages of both -- -- accurate, unambiguous and immune to interference. This hybrid system would be based on the continuous wave technique but would use the spread spectrum technique to resolve the ambiguity problem and be immune to interference.

Before the design characteristics of the hybrid system can be determined, the characteristics of the systems from which it will be derived must be thoroughly understood. Chapter 2 provides a detailed analysis of the characteristics of the continuous wave and two spread spectrum ranging techniques ( FH and DS ) as well as the systems that have been developed from them. An investigation is carried out to determine which of the two spread spectrum techniques is more suitable for integration with the CW system to implement the hybrid system. This thesis then proposes the design specifications of the hybrid system which combines the two techniques.

## Chapter Two

# 2. Continuous Wave And Spread Spectrum

Continuous wave ranging is the simplest form of ranging in that it applies the basic principle of measuring the propagation delay of a periodic wave. Many commercial navigational aids are based on the continuous wave ranging technique. Most of these systems use the hyperbolic method to resolve position.

The primary navigational system used in the aircraft industry is VOR (Very High Frequency Omni-Directional Range), which gives bearing and range of aircraft to beacons located on the ground. OMEGA, developed originally for ships, uses very low frequency radio beams sent out by eight ground based stations around the world. GPS, developed primarily for the military during the "cold war", uses a constellation of 24 satellites which orbit around the earth. These satellites transmit range position information, which upon reception can achieve accuracy of 20 cm (restricted for military use). Recently with "the cold war" no longer being a threat, the applications of GPS were extended to civilian use that yielded accuracy in tens of meters.

The proposed hybrid system will be a combination of the continuous wave and spread spectrum ranging systems. Although both systems determine range by the principle of measuring the propagation delay of the signal; the techniques are different, even though the technique to derive the position from the ranges is similar.

## *2.1 Ranging Principle*

RF ranging systems use the principle of propagation delay to determine distance. The propagation velocity of an RF signal in air can be considered to be a constant. This is close to the speed of light which is $3 \times 10^8$ meters per second. Therefore there is a fixed delay for a signal to travel from point A to point B which is directly proportional to the time delay. Therefore:

$$d = c \cdot t \tag{2.1}$$

Where $d$ = distance in meters; $c$ is speed of light = $3 \times 10^8$ m/sec; and $t$ = time delay in seconds.

A continuous wave system transmits a sinusoidal carrier. Figure 2.1 depicts this signal at the transmitter and the receiver. The delay of this signal in time represents the range as is shown by equation (2.1). This time delay could also be measured in terms of the difference in phase.

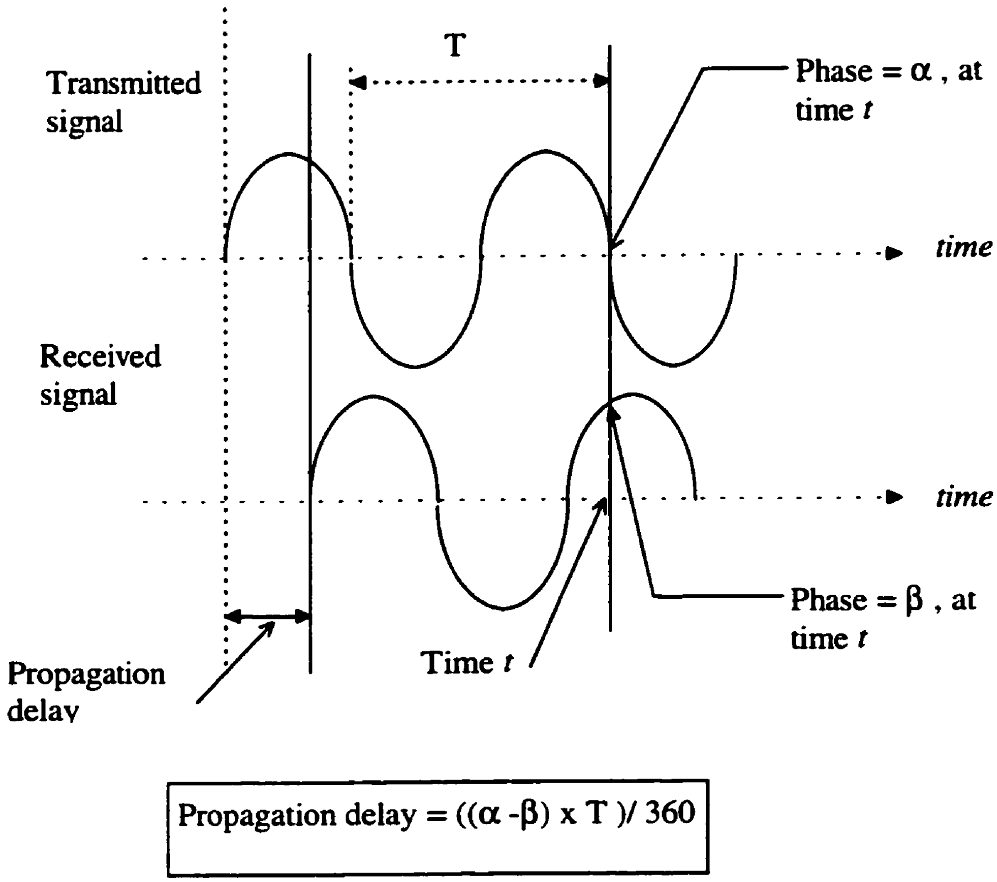



Figure 2.1 Measurement of signal delay

If the phase difference measured was 360° the distance traveled would be the distance spanned by one cycle of the carrier. This distance traveled, called the wave length of the signal, is denoted by λ (lambda), and given by:

$$\lambda = c/f \qquad (2.2)$$

*Where; c = 3 * 10⁸ m/sec and f = frequency of the carrier signal (Hz).*

Therefore the distance traveled by the wave is given by multiplying the phase difference measured at the receiver in degrees by 1/360 of the wavelength. Since the signal is periodic, the phase difference measured is also periodic with 0° being the same as 360°, or 720°, etc. Therefore the distance represented by the phase difference could be any integer number of wavelengths from the transmitter; it is ambiguous. This ambiguity is eliminated in the CW system by having the receiver start at a predetermined distance from the transmitter. As the receiver moves, the wavelength roll-overs are tracked to eliminate the ambiguity. This technique is known as wavelength counting or cycle tracking.

In spread spectrum systems a periodic binary code is transmitted and the propagation delay is measured at the receiver. This delay is also related to the phase of the code seen at the receiver and is shown in Figure 2.2. The main difference between the spread spectrum and the CW technique is that the period of the code is very long and can attain a length which requires one week to repeat. This in turn represents the wave length of the code cycle which is typically thousands of kilometers.

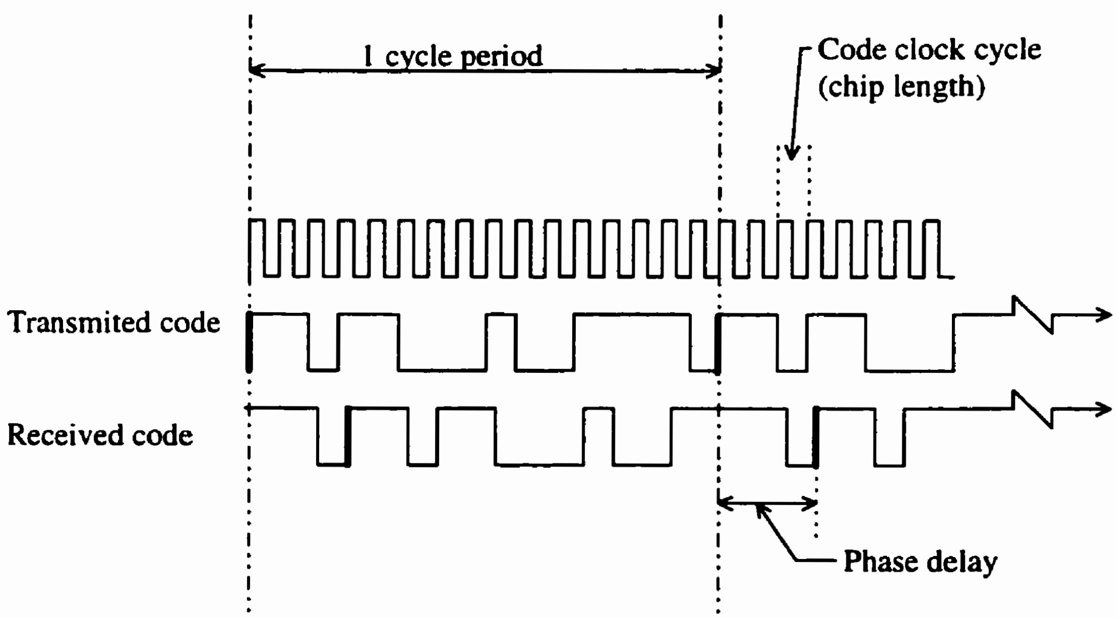



Figure 2.2 Range measurement by spread spectrum system.

The technique to measure the delay is different from that of the CW system. The receiver generates a local replica of the transmitted code; this code is then synchronized in phase with the received code. This phase adjustment at the receiver represents the time delay which is used to derive the range by using equation 2.1. However the resolution of the phase measurement is not continuous; it is in discrete steps of one cycle (chip) of the clock used to generate the code. Since the code modulates the carrier, the clock frequency must be much lower than the carrier's frequency. The resolution of this ranging technique is much larger than that of the CW system.

## 2.2 Achieving Position Fix from distance measurement.

Measuring range from a fixed transmitter using either technique would yield a distance. The loci of the possible fixes would be a circle from the transmitter with a radius equal to this distance. Measuring range from more than one transmitter would then yield multiple circles, whose point of intersection is the position of the receiver with respect to the transmitters.

The phase delay which represents the range can only be obtained by comparing it with a reference. This reference signal is transmitted to the other system entities (beacons). The delay in transmitting the reference signal to each of the beacons is subtracted from the delay of the signal from the beacons to the mobile. There are two delays here, one from the reference station to the beacons to the mobile and the other from the reference station to the mobile. The difference (pseudorange) between these delays is a constant, which produces a loci of possible positions, a hyperbola. Each reference station produces a set of hyperbolas. The intersection of these hyperbolas from each of the stations leads to a position fix at the mobile.

In the CW system the pseudoranges have ambiguities which are resolved by starting over a known point and cycle tracking.

In the spread spectrum system the pseudorange is represented by the difference of the delay of the code reaching the mobile from the beacon and from the master. There are no ambiguities as in the CW system.

## 2.3 Ranging systems

### 2.3.1 CW systems

Land navigation systems are very few and limited. However one existing commercial CWRH (Continuous Wave Reflective Hyperbolic) positioning system can achieve a range accuracy of $\pm 15$ cm. This system is primarily intended for land based, low cost navigation and vehicle guidance [21]. The low cost and accuracy makes this CWRH system an ideal choice as the basis for the hybrid system under consideration. The following detailed investigation of the CWRH positioning system establishes its capabilities and limitations as well as determining its capacity to form the core for the hybrid system.

The CWRH positioning system operates at the low VHF spectrum at 44 MHz. The selection of this particular frequency was based upon the propagation properties of the associated wavelength and the accuracy requirement of $\pm$ 15 cm.

Electromagnetic waves have different propagation properties at different wavelengths. Shorter waves travel in a straight line confined to the line of sight. Longer waves, greater than 10 meters, exhibit diffraction when being transmitted through air which helps them to bend and follow the earth's curvature resulting in a longer travel path than that of the shorter waves. Radio frequencies, when intercepted by conducting objects having dimensions of one, half or quarter wavelength, sets up a resonating field in the object. This resonating field can cause almost total reflection causing a null (blind) spot behind the object. However if the intercepting object is not an ideal conductor a portion of the RF wave is seen on the other side, causing an attenuated signal to be present behind the object. The transmission of shorter waves can be attenuated or absorbed by foliage, trees and other small conductive objects. Wavelengths in the order of centimeters can be absorbed by water particles in clouds, rain and atmospheric moisture. Since the 44 MHz carrier chosen for the CWRH system is at the low end of the VHF spectrum, it exhibits the propagation properties of longer waves of bending and achieving more range than line of sight. Also due to the wavelength being in the order of 7 meters, trees, foliage and clouds have very little effect on propagation resulting in penetration through these obstacles.

With the phase measurement resolution of the CWRH system being 256 steps in one wavelength, the choice of a frequency with a longer wavelength would result in lower accuracy. On the other hand the choice of a shorter wavelength would result in an increase of accuracy but would decrease the stability of phase measurement due to noise.

The system embodies one master transmitter to synchronize the system, three or more beacons (stationary reflective transponders) [17] and a mobile receiver(s). The master transmits a synchronization pulse to time synchronize the reflectors and the mobile receivers. The beacons are uniquely identified in the system with time division multiplexing. The beacons receive and reflect in their allotted time; for example beacon number 1 receives and transmits first after the synchronization pulse.

The master transmits the synchronization pulse with a unique carrier phase sequence; the end of this sequence is the time indication of master to beacon number 1 transmission. The master transmits a known carrier phase for a fixed time, and beacon number 1 receives the carrier. At the end of master to beacon transmission time beacon number 1 transmits the same phase of the carrier as seen at the beacon during the master to beacon 1 transmission period. This process in effect represents a true reflection. This cycle is carried out for all the beacons in the system. After the last beacon transmits the cycle is completed. Completion of the cycle is indicated to the system by a small time interval of dead air where no transmission takes place from any beacon or master. Figure 2.3 illustrates a typical modulation cycle.

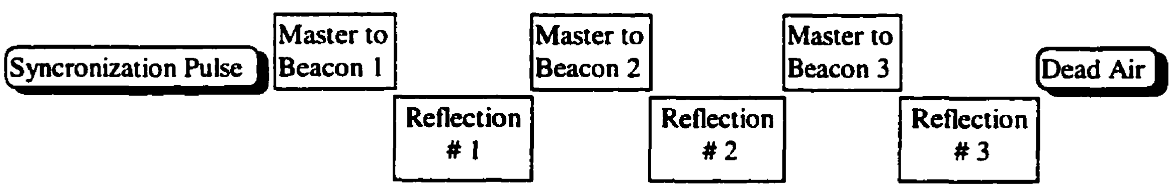



Figure 2.3. Modulation Cycle (87 ms)

The beacons produce an ideal reflection by measuring their own transmitted phase and compensating the next transmission accordingly for any phase delays introduced in the receive section of the beacon. The reflectors also adjust the drift in the oscillators by constantly adjusting the onboard reference oscillator to that of the master. The phase of the carrier transmitted by the reflector, as seen at the master relative to the reference oscillator of the master, is indicative of the distance between the master and the reflector. The phase difference is caused by the delay in propagation, and hence the phase difference can be translated to range distance using the speed of light.

The mobile receivers synchronize to the master and receive the transmission of the master and the reflectors. After synchronization the phase of the master to beacon transmission and beacon reflection is measured. The phase received by the mobile represents the direct path from master to mobile and the roundabout path from master-to-beacon-to-mobile. This is depicted in Figure 2.4.

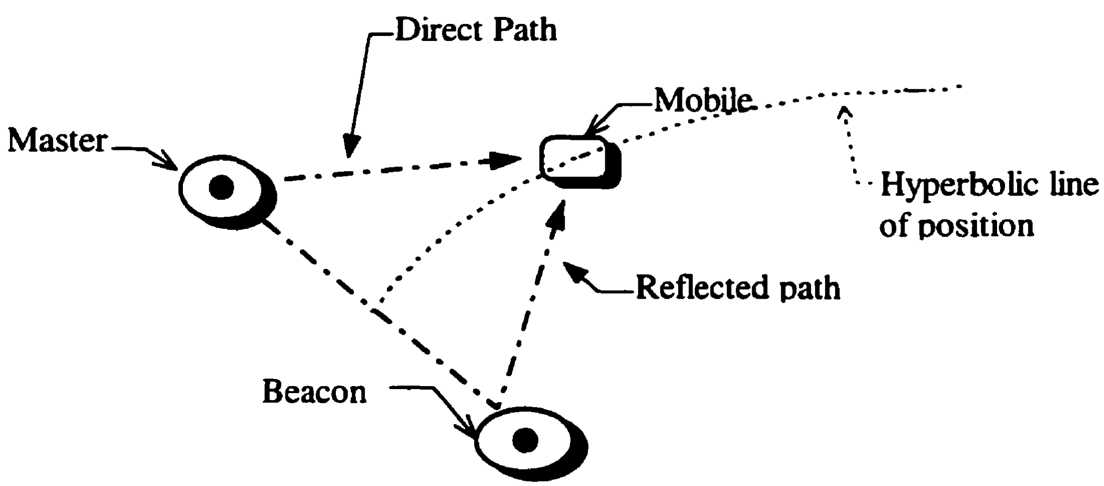



Figure 2.4 Reception of signal at mobile

The difference in phase of these two signals (direct and reflected) is constant over a hyperbola passing through the mobile ( Figure 2.4 ). The intersection of two or more hyperbolas created by other beacons can determine the position of the mobile, relative to the known fixed positions of the master and the beacons.

The beacons and the mobiles must measure the phase of the received carrier very precisely to yield an accuracy of ± 15 cm. The beacons have to be precise in measuring the received phase and offsetting the transmitted carrier phase in order to achieve ideal reflection, whereas the mobile has to only measure the received phase accurately to determine its position. The method by which the system achieves this accuracy in phase measurement can be shown by a detailed analysis of the operation of the beacon. The beacon in the CWRH system contains both the transmitter and the receiver, which are present in the master and the mobile respectively. The block diagram of the beacon used in the CWRH system is shown in Figure 2.5.

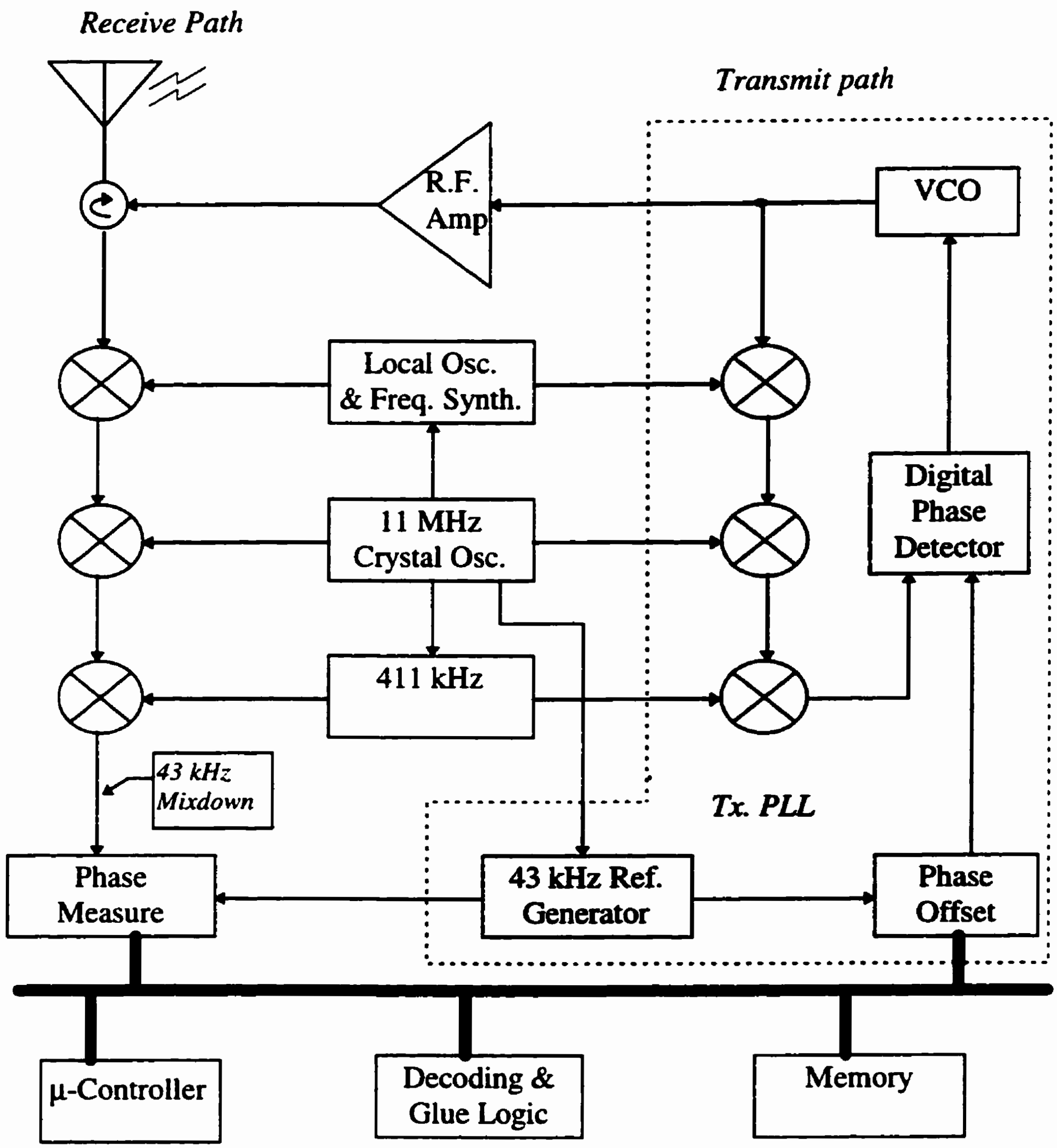



Figure 2.5 Internal block diagram of the beacon in the CWRH system.

The block diagram shows the different mixdown stages for the receive section and the transmit section. The shaded area shows the transmit section of the beacon. The receive path is shown on the left hand side of the figure.

The receive section consists of three mixers with local oscillators derived from one common reference (11 MHz Oscillator). The received carrier is mixed down to a low frequency signal of 43 kHz which is then fed into a phase-measurement circuit. The phase-measurement circuit reads the phase of the 43 kHz signal with respect to the reference 43 kHz signal derived from the stable crystal oscillator. This phase of the mixed down 43 kHz signal is a direct representation of the phase of the received carrier [20]. The block diagram of the phase-measurement circuit is shown in Figure 2.6.

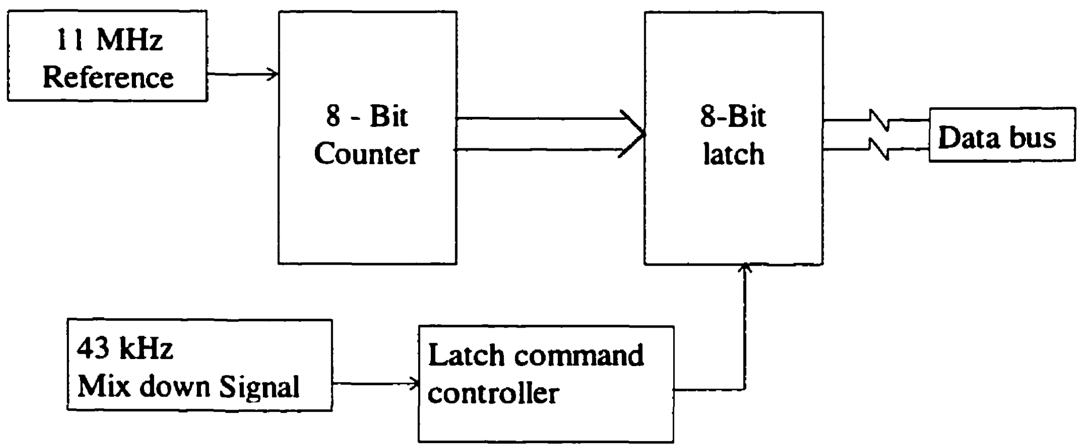



Figure 2.6 Phase-measurement circuit for CWRH system

The reference 11 MHz signal, when divided by 256, gives the reference 43 kHz signal. The 8 bit counter achieves this division and provides 256 different states of one 43 kHz cycle. The rising edge of the mixdown 43 kHz is used to latch the counter state. This state is the phase of the local 43 kHz (reference) when the rising edge of the received 43 kHz occurs. The latch command controller, registers the count to the data bus on the negative edge of the 11 MHz clock (assuming the counter operates on the positive edge of the clock) to ensure a stable counter state and synchronization with the11 MHz clock.

The transmit section uses the locally generated reference 43 kHz signal and the same local oscillators as the receive section to generate the carrier frequency. The stability of the generated carrier is maintained by the phase locked loop shown in the shaded portion of Figure 2.5. The transmit section also has the capability of offsetting the phase digitally to any $1/256^{th}$ part of the 43 kHz reference. This is achieved by the phase locked loop formed by the VCO, the phase detector and the mixers. Changing the phase of the reference in a phase locked loop changes the phase of the output frequency. During transmission, the phase of the reference is offset using an 8 bit counter and an 8 bit digital comparator. The value of the desired phase is loaded on to one port of the comparator and the output of the counter is loaded on the other port. The output of the comparator is a pulse wave form of 43 kHz. This 43 kHz signal is the reference input of a digital phase detector, which is a part of the transmit phase locked loop.

Accurate reflection of received phase at the beacon is achieved measuring the phase of a transmitted carrier. The system performs a compensation check by determining the difference in the phase value measured to the desired phase value transmitted. This difference in phase is then adjusted appropriately for the next transmission of the carrier.

The CWRH system has the advantage of measuring the phase very accurately to 1/256th of a wave length, resulting in a basic resolution of 2.6 cm for a wave length of 6.81 meters. After accounting for the system and measurement noise the CWRH achieves an accuracy of ± 15 cm. Although the accuracy of the system is very high, there is an ambiguity for a distance of more than a wave length. This ambiguity is resolved by tracking the velocity of the mobile and counting the wavelengths after initializing over a known position. The process of initializing is a limitation of the system due to the fact that in the event of losing track of the wave length due to signal loss or multipath the ability of position locating is lost. This could be improved by the spread spectrum technique which is capable of operating in noisy conditions.

### 2.3.2 Spread Spectrum systems

Spread spectrum techniques date back to pre-World War II years, and at that time its usage was considered to be a highly classified activity[4]. The term "spread spectrum" is used to describe a technique or a group of modulation techniques which deliberately employ large bandwidths to send relatively small amounts of information. A spread spectrum system is classified by two basic criteria[5]:

a) The transmitted bandwidth is much larger than the bandwidth of the information being sent.

b) Some function other than the information being transmitted is employed to determine the resultant transmitted signal bandwidth.

The spreading of the spectrum or transmitting a bandwidth larger than the information sent is achieved by modulating the carrier with a signal having a large bandwidth (e.g., square wave).

The purpose and applicability of spread spectrum techniques are fourfold[6]:

- undetectable transmission
- interference suppression
- energy density reduction
- ranging or time delay measurements.

The ability to transmit without occupying any one frequency is advantageous for many military applications where transmission must be undetectable by the enemy. This is achieved by spreading the carrier and occupying a larger bandwidth compared to the base band signal.

Interference suppression is the major advantage of spread spectrum systems. Protection against jamming (intentional or unintentional) enables two or more spread spectrum systems to transmit simultaneously at the same carrier frequency but using different codes to spread the carrier. This simultaneous transmission of many channels is known as CDMA (code-division-multiple-access). Another form of interference, suppressed by spread spectrum systems, is the self interference caused by multipath in which delayed versions of the signal, arriving via alternate paths, interfere with the direct path transmissions.

Reduction of the energy density of the transmitted signal helps to meet international spectrum allocation regulation requirements, minimizes detectability and maintains privacy of transmitted data. By spreading the signal energy over a wider bandwidth, total transmitted power can be increased, resulting in improved performance.

Ranging or time delay measurements applied to position location using spread spectrum techniques is rapidly gaining popularity. The spread spectrum signal used for ranging is a long sequence of polarity changes (binary PSK modulation). Upon reception, this is corrected against a local replica and “lined up” to perform an accurate range or delay measurement[7]. The PN (pseudo-noise) code has a long cycle and the phase of the cycle is unique and can be easily determined during synchronization at the receiver. Range measurement is achieved by measuring the phase delay of the code between the receiver and the transmitter.

In spread spectrum systems the ratio of the spread or transmitted bandwidth to the rate of the information sent is called “Processing Gain”. A system with 33 dB processing gain would offer a 33 dB improvement in signal to noise ratio between the receiver RF input and the baseband output.

Figure 2.7 illustrates a basic PN encoded transmitter[6]. The data from the source is coded by an appropriate coding scheme and modulated on to the carrier, which in turn is modulated by the PN code. This modulated signal has a bandwidth many times larger than the data bandwidth. The signal is intercepted by the receiver antenna and fed to the PN acquisition circuit. The receiver generates the same PN code as generated by the transmitter. The locally generated code is tested with the received signal for each possible code phase until they are synchronized. This locally generated code is used to cancel the PN code of the received signal, thus reducing the spectrum to the original data bandwidth.

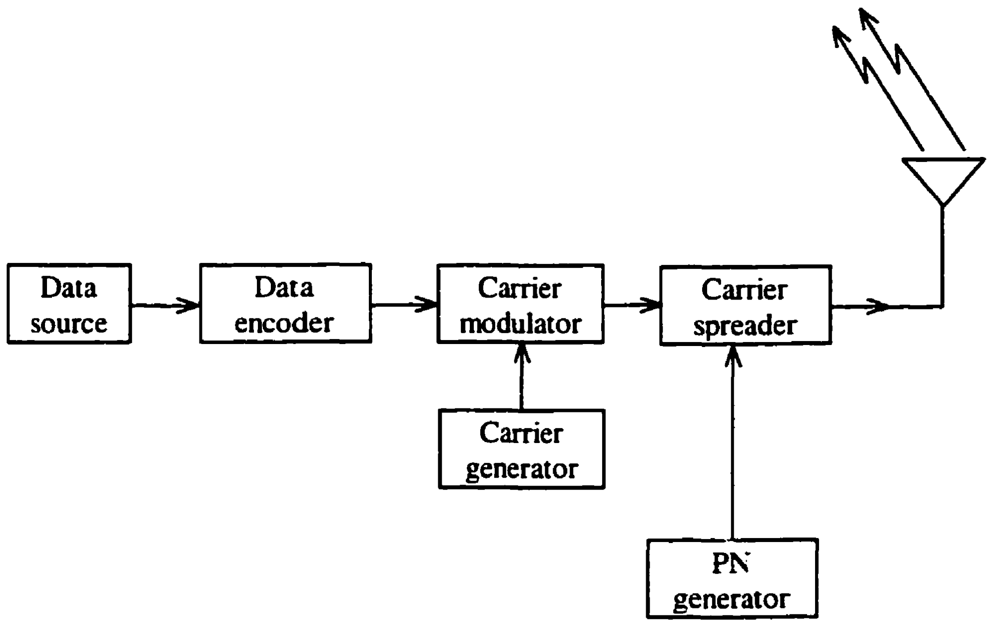



Figure 2.7 Typical spread spectrum transmitter

Selection of the PN code used for modulation in a spread spectrum system determines the reliability and efficiency of the system. The PN code generator used in any spread spectrum modulation technique should have the following properties[8].

- Protection against interference. Coding enables a bandwidth tradeoff: processing gain versus interfering signals.
- Provision for privacy. Coding enables protection of signals from eavesdropping to the degree that the codes themselves are secured.
- Noise effect reduction. Error-detection and correction codes can reduce the effects of noise and interference.

There are several methods of obtaining these PN codes as suggested by Baumert, Easterling, Goulomb and Viterbi, A.[9], Gold [10], Painter[11], Peterson [12], and many other authors.

Using these binary codes there are two basic types of modulation techniques: frequency hopping, and direct sequence.

"Frequency hopping" modulation is more accurately termed as "multiple frequency, code selected, FSK (frequency shift keying)". This means that a Frequency Hopping system utilizes more than two frequencies to perform FSK (as opposed to only two frequencies in a normal FSK system) and the shifting from one frequency to another is determined by a preset code. Typical Frequency hopping systems have a number of frequencies available, which are selected on the basis of the PN code in combination with the data to be transmitted [8]. A frequency hopping system basically consists of a PN code generator and a frequency synthesizer capable of responding to the code. Ideally the instantaneous output is a single frequency. A typical frequency hopping system is as shown in Figure 2.8.

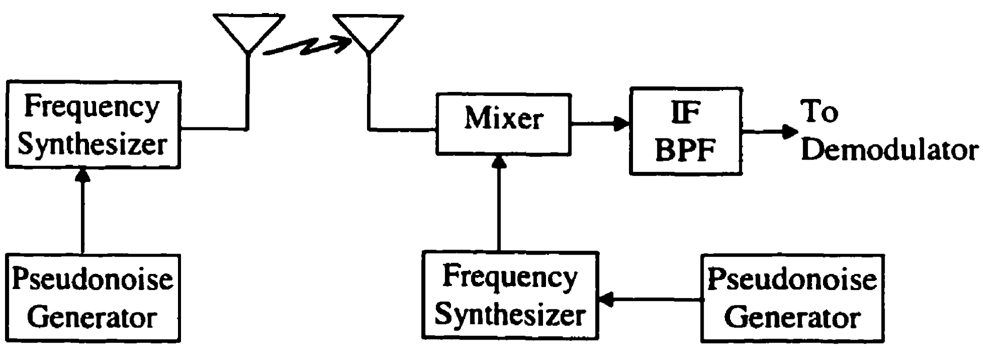
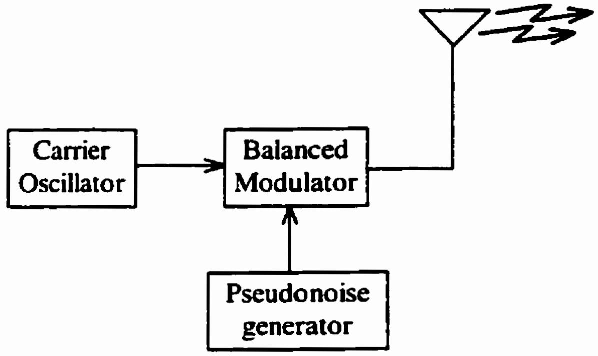



Figure 2.8 Basic Frequency Hopping System

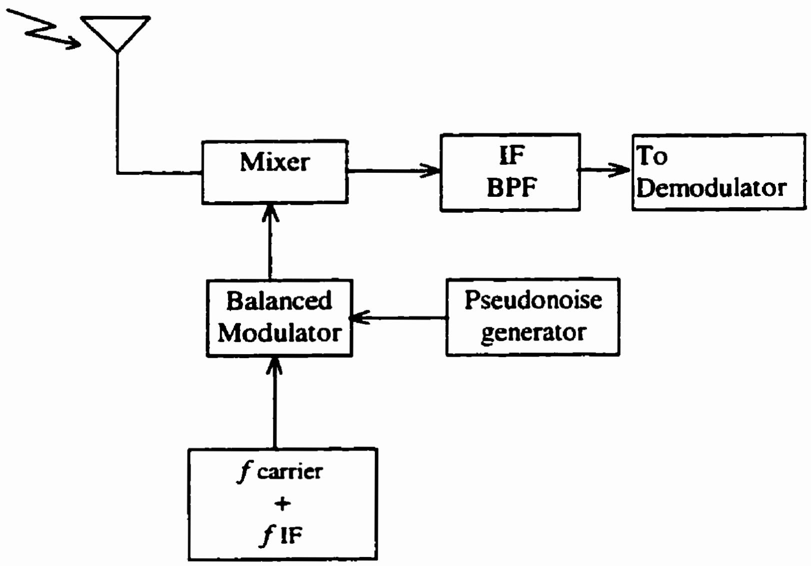
The main disadvantage of a frequency hopping system is the inability to achieve high chip rates for the code: frequency synthesis at rates higher than 1 Mcps (Mega chips per second) is almost impossible or very complicated to implement. A typical frequency hopping spread spectrum system has the chip rates in kilochips to hundred kilochips per second. Because of these lower chip rates the range resolution of frequency hopping systems is very poor [8]. Thus position location is not a commonly used application for frequency hopping spread spectrum systems. However there is a proposal for applying FH to ranging systems suggested by Toth [18].

Direct sequence systems employ a high speed code sequence, in addition to the base band information, to modulate the carrier using double sideband suppressed carrier techniques. In the general case the modulation may be AM (pulse), FM, or any other amplitude- or angle-modulation form. However the most common method is 180 degree bi-phase modulation.

The direct-sequence receiver multiplies the received signal with a locally generated replica. Assuming that the transmitter and the receiver code are synchronous, the carrier inversions transmitted are removed and the original carrier is restored. This narrow band carrier is then passed through a bandpass filter, which passes only baseband modulated carrier. Any received signal, not synchronous with the coded reference of the receiver, is spread to a bandwidth equal to its own bandwidth plus the bandwidth of the reference. This ensures that the bandpass filter can reject almost all the power of the undesired signal. This mechanism of multiplication and filtering provides the desired signal with an advantage or "process gain". Figure 2.9 shows a typical direct-sequence system.




**a) Transmitter**




**b) Receiver**

Figure 2.9 Direct sequence spread spectrum system. a) Transmitter ; b) Receiver

The implementation of a direct sequence spread spectrum system is not as complicated as that of the frequency hopping system. The PN code can be generated using standard digital logic, and the spreading of the carrier is achieved by modulating the digital code using a double balanced mixer. The receiver in a direct sequence system can also implement digital techniques for synchronization. This ability of direct sequence spread spectrum systems to implement higher chip rates and the ease of implementation makes direct sequence techniques a better choice over the frequency hopping technique as a partner for the CWRH system.

To achieve a position fix a typical direct sequence spread spectrum ranging system would use the same hyperbolic method as the CWRH system. The system consists of a master and more than two reflective transponders (beacons). The master transmits the spread carrier to which all the transponders and the mobiles synchronize. The beacons measure the phase of the code received after synchronizing to the master transmission. This phase is then set as the transmit code phase, during beacon transmission time. The PN code transmitted by the beacon could be the same as that of the master's, or a different code (CDMA). The mobile receives signals from the master and the beacon and synchronizes accordingly. Setting the phase of the code received from the master as a reference, the difference of the phase received from the beacons to this reference is measured. This difference is then used to calculate a pseudorange. Several pseudoranges from several beacons form the loci of multiple hyperbolas which intersect and determine the mobile's position. If the same code is used by the beacons to transmit the reflection from the master, the master transmit time and the beacon transmit time must be distinct in order for the mobile to distinguish the different transmissions.

Direct sequence systems have been applied in space exploration programs since the 1960s. The military is a major user of spread spectrum; one such system is the TDRSS (Tracking and Data Relay Satellite System). This system employs two separate spread spectrum signals transmitted simultaneously. One signal is a 1023 chip long Gold code bi-phase modulated carrier and the other is also bi-phase modulated carrier, but with a linear maximal code whose length is 261,888 (256 x 1023). This is obtained by truncating a normal $2^{18}$-1 code. The two carriers are sent simultaneously at the same frequency, but the long code is modulated to the quadrature phase carrier of the 1023 code. The receiver then treats these two signals as independent bi-phase signals.

GPS, derived from the TDRSS technique, is another system using spread spectrum. This system uses a constellation of 24 satellites, each in a 12 hour orbit, with up to six satellites in view at any given time[16]. Each of the satellites generate two L-band carriers, namely L1 - 1575.42 MHz and L2 - 1227.6 MHz. Similar to the TDRSS system, there is a 1023 chip Gold code, and a $6.19 \times 10^{12}$ chip (one week long) code. The short code is known as the "clear access or C/A code", also known as the Coarse Acquisition code. The long code is known as the "Protected or the P" code, also known as the Precision code. Figure 2.10 shows the transmitter block diagram for a GPS satellite.

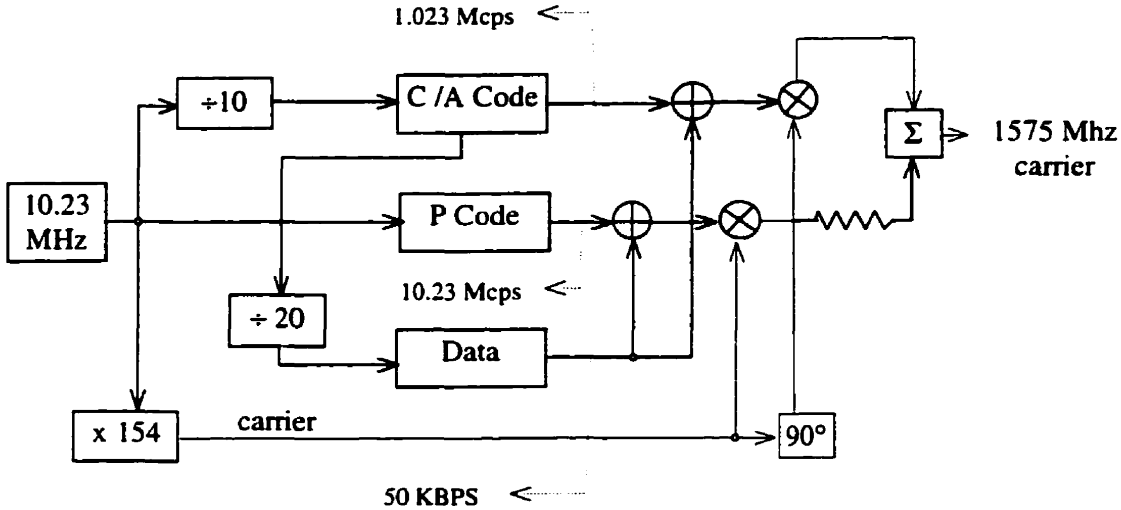



Figure 2.10 Satellite transmitter for GPS system. [8]

The L1 carrier is bi-phase modulated with the short code, and the long code bi-phase modulates the quadrature phase of the L1 carrier. The L2 carrier gets bi-phase modulated by the same long code. Further, the 1023-chip short code is divided to provide a 50 kHz clock for data transmission. The data provides information for the receivers to synchronize to the long code.

The GPS system used by the military transmits positioning information along with other data from the satellites over such large distance in noisy conditions. The receivers on the ground are able to obtain their current position by effectively filtering out the noise and deriving the positioning information from the satellites. This shows that the GPS system using the direct sequence technique can achieve satisfactory signal reception with low SNR (signal to noise ratio). Therefore direct sequence systems are most suited for ranging for their ability to reject noise and to resolve range to within a chip of the PN code. Applications have been developed using GPS to guide military personnel and vehicles to perform tactical operations. There are other civilian uses, to which only the

C/A code is available, for sports, rescue teams, etc. Because the P code is not available for civilian use, achieving submeter accuracy with GPS system is quite complicated. A different system could be implemented using similar direct sequence techniques, that would meet or exceed the accuracy of the military version of GPS. Even higher accuracy can be obtained if the phase of the carrier is measured. The CWRH system has the capability of measuring phase of the carrier to within 1/256th of a carrier cycle.

If a hybrid system is developed to integrate the direct sequence techniques with the CWRH system the advantages of the GPS system can be incorporated in the CWRH system. Also since the chip rate required is not very high, the implementation can be achieved on relatively low speed logic.

## 2.4 Direct sequence spread spectrum and CWRH system

Table 2.1 shows a comparison of the two ranging techniques; continuous wave and direct sequence spread spectrum. The comparison indicates that the advantages of spread spectrum could be used by a continuous wave system to provide improved performance and reliability. The spreading of the carrier over a wide band of frequencies minimizes the problems of multipath nulls and interference inherent in continuous wave systems.

Table 2.1. Comparison of ranging techniques.

| **Continuous wave** | **Direct-sequence Spread spectrum** |
|---|---|
| Ambiguity over one wave length | Ambiguity only over large distances (depends on the code cycle) |
| Good resolution within one wavelength. | Range resolution depends on code rate |
| bandwidth as big as data | More noise like (therefore undetectable transmission) |
| Must have positive S/N | Can operate below ambient noise |
| Simple synchronization required to receive signal | Synchronization more difficult |

The CWRH system can measure phase very accurately to within one cycle, but still has the limitation of being unable to resolve the ambiguity of distances larger than one carrier cycle without enhancements. The system currently resolves the ambiguity by initializing the mobile over a known location and subsequently tracking the wavelengths. Due to the utilization of single frequency the system is subject to multipath and fading which could lead to incorrect tracking, resulting in loss of position.

As requirements for covering larger areas increases for the CWRH, the transmit power must also increase. The problems associated with higher power transmission are: more complex design, higher system power requirement, higher towers for stationary transmitters and more interference for other RF receivers such as TV and mobile radios operating at the harmonic frequency of the CWRH system.

Spread spectrum techniques provide solutions to some of the mentioned problems. Direct sequence spread spectrum systems are particularly known for their ranging application. The code cycle frequency, being very low, has an effective wavelength of several kilometers, which solves the problem of ambiguous range for the continuous wave system. If a spread spectrum system was to operate at the CWRH operating frequency and if it could synchronize the Pseudonoise code to within less than half the carrier cycle; the phase of the carrier could be measured. This method could yield the accuracy of the CWRH system while maintaining the features of spread spectrum.

The spread spectrum system also has an added advantage of process gain and resistance to jamming, which the continuous wave system lacks. The process gain of the hybrid system is determined by the rate of information transmitted, which is the duration of correlation of the received signal. Since there is no data transmission, the processing gain achieved by the system is very high. This results in a good signal to noise ratio of the received signal which leads to a wider coverage area or larger range of reception for an equivalent transmit power. A hybrid system combining the continuous wave and direct-sequence spread spectrum techniques would provide a good compromise in range resolution and the advantages of a spread spectrum system.

This thesis investigates and proposes the implementation of the hybrid ranging system using the existing CWRH system and the direct sequence spread spectrum system. The hybrid system combines the advantages of the CWRH system with that of the Spread Spectrum system. The hybrid system has to perform all the functions of a Direct Sequence Spread Spectrum system and also accurately measure the phase of the carrier. The requirement of having high chip rates to obtain a higher resolution is not necessary if the PN code synchronization can be achieved to within one degree of phase of the chip. It has been shown that it is possible to synchronize to within 1/1000th of a chip [19].

Figure 2.11 shows a graphical representation of different ranging techniques investigated, and the resulting hybrid ranging system is a combination of two commonly used ranging techniques.

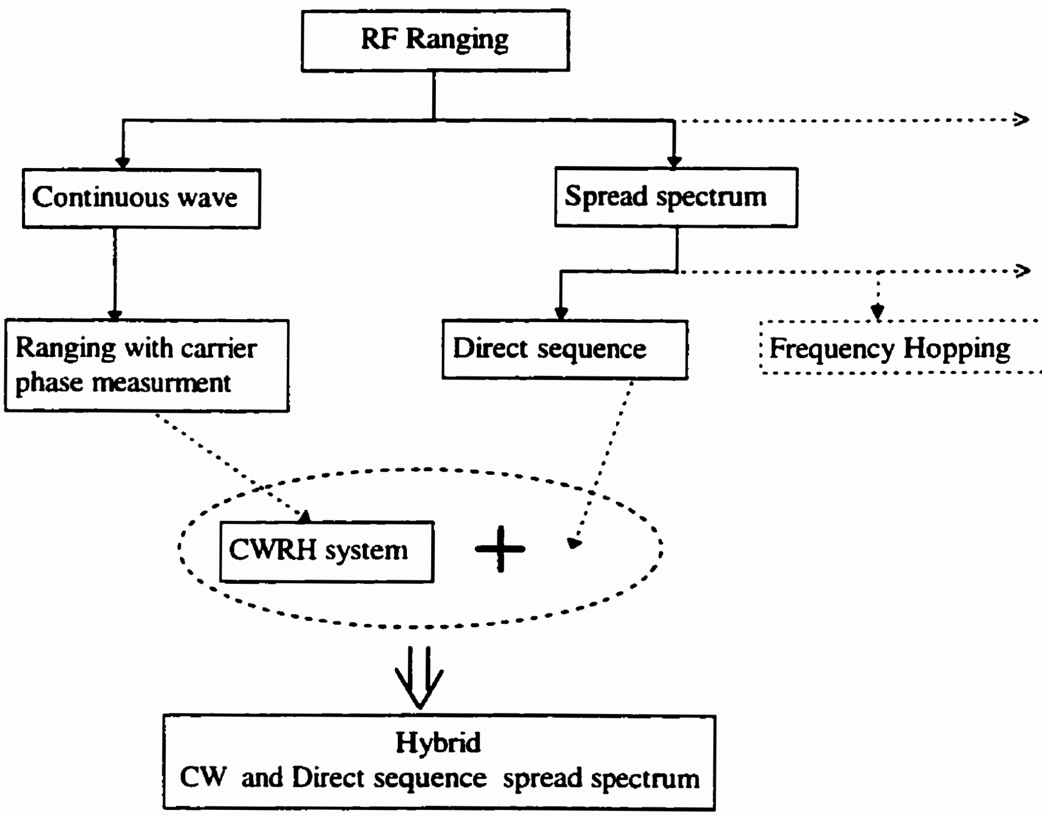



Figure 2.11 Flow chart for hybrid ranging system derivation

## Chapter 3

# 3. The Hybrid system

Practical and efficient applications of precise positioning and navigating for farming, driverless vehicles and mapping, demands a system which has both the accuracy of the CWRH system and the robustness of the direct sequence spread spectrum technique.

The hybrid system incorporates direct sequence spread spectrum to overcome the ambiguity problem and to improve the system's immunity against interference. The hybrid system can be implemented by either taking an existing DSSS system and adding the accurate carrier phase measurement components to it or, alternatively, by adding components to an existing CW system to perform the spread spectrum transmission and reception. Since the CWRH system is closely linked to the CW ranging technique and has the components for measuring the phase of the carrier accurately the latter approach of adding the spread spectrum components to it is chosen. The ranging technique and the modules (master, beacon and mobile) used for the hybrid system would be similar to those of the CWRH system.

The CW system has the following specification which the hybrid system should meet or exceed. Table 3.1 shows the current specifications and the desired specifications from the hybrid system.

Table 3.1 List of CW specifications applicable to the hybrid system.

| | Current CW specification | Desired Hybrid system specification |
|---|---|---|
| **Range Resolution** | 3 cm | 3 cm |
| **Operating range radius around master** | 20 Km | > 20 Km |
| **Number of beacons in the system** | 8 | 8 |
| **Range update rate (for 8 beacons)** | 6.25 ranges per second | ≥ 6.25 ranges per second |

Regarding these specification and using the spread spectrum modulating technique the hybrid system would require the following functions to achieve a position fix.

I. Measuring carrier phase accurately.

II. Spreading the carrier for transmission.

III. Despreading the received signal.

IV. Synchronizing and correlating to determine the phase of the transmitted code.

To convert the existing CWRH system to incorporate the direct sequence spread spectrum technique, items II, III and IV of the above list must be added. The components needed to achieve the spreading of the carrier are a bi-phase modulator and a PN code generator. Despreading is achieved with another bi-phase modulator as used for spreading the carrier along with another PN code generator. The correlation and synchronization of the PN code at the receiver is achieved by a PN code phase shifter and a correlation detector to measure the degree of synchronization.

Before the components required to convert the CWRH system are described in detail, the function of the hybrid system modules are reviewed briefly. This functional description, although similar to the CWRH system, will clarify the technique used to obtain a position fix from the difference in phase of the PN code and the carrier.

## 3.1 Ranging Technique

The proposed ranging technique for the hybrid system will have the ability to measure the phase of the carrier like the CWRH system, and also have the ability to measure the phase of the PN code. The PN code, which has a slow repetition rate, effectively has a wavelength which is longer than the operating distance of the system. The measurement of phase within this effective long wave length enables the hybrid system to overcome the ambiguity of the CWRH system.

Similar to the CWRH system, the proposed hybrid system consists of a master, more than two beacons and multiple mobiles. The mobiles derive their position from the propagation delay of the signals received from the master and the beacons. The master's transmission is used to transmit the timing information to synchronize the beacons and the mobiles. The master's transmitted carrier is also used to align the reference clocks on all other receivers. A typical setup of the system is shown in figure 3.1

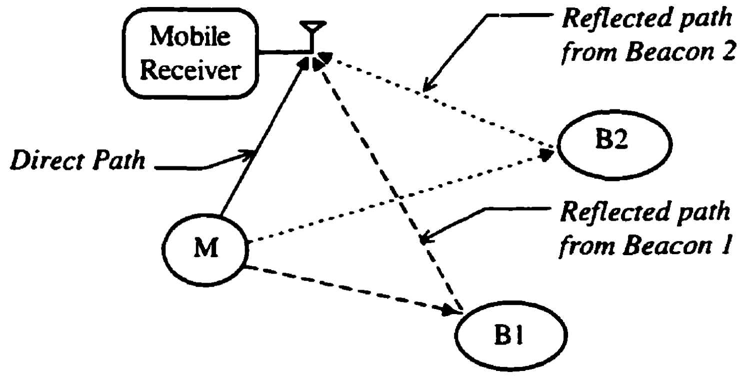



Figure 3.1 Hybrid system setup

The master and the beacons which are the stationary parts of the system are installed over known locations (co-ordinates). This information is known to the mobiles and is used to derive their position. Ranging in the hybrid system is achieved as follows:

- Master: The master transmits the carrier with no phase modulation other than the modulation due to the PN code. The phase of the carrier transmitted and the phase of the PN code used to modulate the carrier is considered to be zero degrees by the beacons and the mobiles.

- Beacon: The beacon acts as an ideal reflector by transmitting the received signal from the master. It receives the spread carrier and adjusts its local PN code to synchronize with the received signal. The adjustment or the offset required to synchronize, is the propagation delay of the transmitted PN code. Once synchronized the local PN code should be within half a cycle of the carrier, whose phase is measured with the same technique as the CWRH system. This measured phase of the carrier and the PN code is then used to set the transmit section's carrier and the PN code. The beacon then transmits a carrier with the proper phase offset and modulated with the PN code. This process is termed as "reflection" of the received signal.

To achieve a perfect reflection the beacon must adjust the transmit phase to be the same as that measured at the antenna during reception from the master. This adjustment compensates for the signal delay which occurs from the antenna through the receiver and back to the antenna. This delay should be zero, which is not the case and has a finite value; however it can be made to have an apparent delay of zero by adjusting the phase of the transmitted signal. This delay does not have a significant effect on the phase of the PN code. It is the carrier's phase that requires compensation [21,15]. The amount of compensation can be considered to be constant over short periods of time and adjustments to then are only necessary periodically.

<u>Mobile</u>: The mobile receives from the master and all the beacons in the system. The master's transmission is used to synchronize the system's timing and is used to measure the phase of PN code and the phase of the carrier. The mobile then receives from beacon 1. The phase of the received carrier and the PN code measured from the beacon transmission is compared to the phase measurements of the master's transmission. The difference of the phases is indicative of a pseudo-range. A pseudo-range is the distance of the path from master-to-beacon-to-mobile minus the path from master-to-mobile. This difference is calculated for all the master beacon pairs which puts the mobile on a hyperbolic (LOP) line-of-position for each pair, as shown in Figure 3.1.

The intersections of these different hyperbolic LOPs results in the position of the mobile.

The proposed hybrid system uses only a single channel for receiving from different transmitters. This necessitates the use of a multiplexing technique to allow the mobiles and the beacons to receive on a single channel. The existing CWRH system uses TDM where each transmitter is assigned a time slot. The hybrid system could use the same timing as that of the CWRH system. However since the hybrid system uses spread spectrum to transmit, it has the advantage of using other multiplexing techniques such as CDM ( Code Division Multiplexing). The reason for considering CDM would be to reduce the modulation cycle which would increase the rate of position fixes. Before the timing of the hybrid system is determined a closer examination of CDM will determine its effectiveness for the hybrid.

For single channel systems employing spread carrier transmission, one form of multiplexing that could be considered is CDM (code division multiplexing). Code division multiplexing is the ability to transmit multiple spread carriers on the same channel. The PN codes used for spreading the carrier are unique for each transmitter. However the receiver has aprior knowledge of them. All signals other than the one being received, appear as interference or noise and are rejected. Spread spectrum ranging systems commonly use CDM for multiplexing among beacons. Each transmitter in the system utilizes a unique PN code to spread the carrier. The receiver selectively tunes to a particular transmitter by despreading the received signal with the same PN code as that of the transmitter. This selective tuning is known as correlation. This selective tuning is only effective when all the codes used in the system are such that the receiver can uniquely identify each transmission. Therefore the code selected should satisfy the condition for CDM.

An alternate method for multiplexing can be achieved by using a combination of TDM and CDM. With this method the transmitters are identified uniquely by the phase of the code. The code transmissions are staggered in time. The amount of staggering depends upon the maximum propagation delay the code has for the operating range of the system. The code staggering is selected so that the receiver cannot synchronize to more than one phase delayed transmission. This technique provides the use of a single code in the system, but requires one master to synchronize the transmission times of all other beacons. This method can be graphically represented as shown in Figure 3.2.

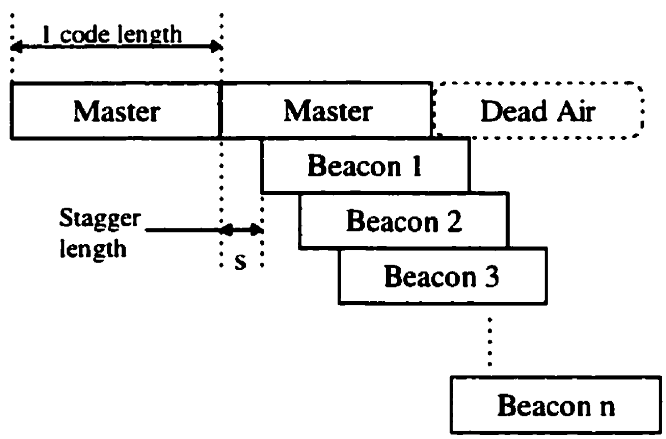



Figure 3.2 Staggered system timing scheme

The Master transmits for two complete PN code cycles, and then ceases transmission for one code cycle. This marks the synchronization time for all the beacons and the mobile units. Beacon number 1 synchronizes with the master, and the phase of the PN code and the carrier is measured. Beacon 1 reflects the same PN code phase and the carrier phase at $1/s^{th}$ of the second cycle of master transmission. The beacon transmits for one code cycle and pauses for two full code cycles. The other beacons follow Beacon 1, separated by $1/s^{th}$ code length from each other. The separation of transmitting time between the beacons is set to ensure unambiguous code phase for the operational range of the hybrid system. The desired operational range for the hybrid system from Table 3.1 is currently specified to be greater than 25 km; therefore selecting a value of 50 km would provide adequate coverage.

The rate and length of the code to be used for the proposed technique will determine the amount of code length separation from one beacon transmission to the other. The type of code selected should have a unique correlation to facilitate transmission of more than one beacon at the same time. The details of the proposed multiplexing technique for the hybrid system are then given in section 3.2.1.3, after the type of PN code has been selected.

## 3.2 The Hybrid System Components

The Beacon in the hybrid system contains both, the hardware for transmitting and receiving, whereas the master contains only the transmitter and the mobile contains only the receiver. Therefore all the components required to convert the CWRH system to the hybrid system can be discussed by using the beacon.

To achieve the functionality of carrier spreading, a modulator is required which can flip the phase of the carrier corresponding to the PN code. A PN code generator is attached to one input of the modulator. The modulator and the PN code generator are the two main components of the transmit section. The receive section requires a despreader to despread the received spread carrier. This is achieved by a modulator similar to that used in the transmit section. The modulator modulates the incoming spread signal with a PN code, generated at the receiver. If this PN code is in phase with the received signal, the output of the modulator is the despread carrier. The received PN code's phase is subject to a propagation delay which is unknown. Thus in order to adjust for this phase delay, a code phase shifter is required. The amount of shifting required is controlled by the correlation detector whose output is proportional to the offset in synchronization of the received PN code to the local PN code. These two components; the code shifter and the correlation detector form the synchronization circuit.

Figure 3.3 shows the block diagram for the proposed hybrid system. The shaded blocks in the figure indicate the additional components needed to perform the above functions. The components required for this operation are indicated by dotted box in the Figure 3.3.

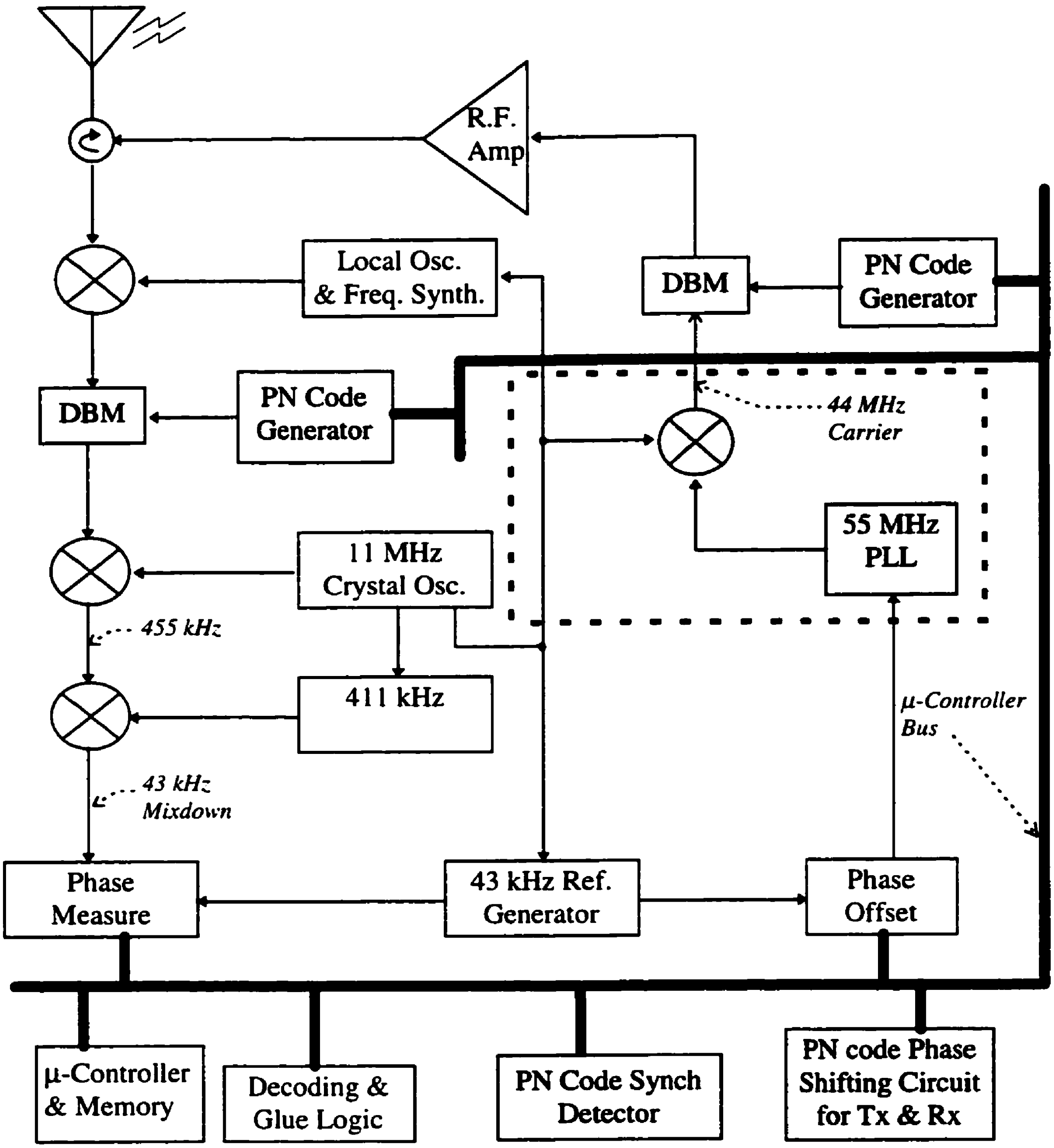



Figure 3.3 The proposed hybrid system
(Components added to the CWRH system are shown in the shaded regions)

### 3.2.1 PN code Generation

The critical element of any spread spectrum system is the PN code. It determines how the carrier is spread. The selection of the code can affect the operational range and the process gain of the system. The code selected will also affect the degree of noise immunity the system can achieve. Before a code generation method is chosen, the chip rate, the length of the code, and the type of code must be established.

#### *3.2.1.1 Selection chip rate and length of the PN Code*

It is desired that the proposed hybrid system will achieve the desired specifications in Table 3.1. Since the same phase measurement technique as that of the CWRH system is used, range resolution of 3 cm should be achievable. This is required for applications intended for surveying [14] and vehicle guidance [21].

To eliminate the carrier cycle ambiguity of the CWRH system the receiver should have the capability of synchronizing the local PN code to within less than half the duration of a carrier cycle from perfect synchronization. This would ensure that the carrier phase measured is the unambiguous phase from the point of full synchronization of the code. The number of carrier cycles in a chip basically determines the chip rate of the PN code. Some systems can achieve synchronization to within $1/1000^{th}$ of a chip [19]. The proposed hybrid system is designed to synchronize and measure to within 1/256th of a chip. This 1/256th of a chip should establish carrier phase measurement to less than half of the carrier cycle to avoid any ambiguity. Setting the system carrier to be 44.56 MHz, then one cycle duration is 22.44 nano seconds, and a half cycle is 11.22 nano seconds. To achieve synchronization to within half the carrier cycle in 256 steps, a chip of width

2.873 μsec ( [11.22] * 256 ) or a chip rate of 348.125 kHz results. This would be the lowest chip rate. To overcome the ambiguity resolution based on the synchronization to within 1/256 of a chip.

Since the chip rate is directly proportional to the processing gain of the system a higher chip rate would be desired. However a higher chip rate would also increase the transmitted signal bandwidth which would be physically limited by the system. For a typical spread spectrum system the main lobe of the sinx/x spectrum is transmitted which is two times the chip rate. Assuming that the transmit bandwidth is to be less than 2 MHz; then the chiprate must be less than 1 MHz. Another consideration when selecting the chip rate would be the coherency of the chiprate with the reference clock (11 MHz). The desired chip rate will have a value between 1 MHz and 384 kHz and be coherent with the 11 MHz crystal reference. To have a coherent signal the reference should be used to generate the clock for the code generator. Dividing the reference and mixing is a common technique to achieve coherency. The following equation shows how two signals, which are derivatives of the crystal frequency, can be added to yield a chip clock frequency of 738.0789 kHz.

Crystal frequency = 11.114600 MHz

$$\text{chip clock frequency} = \frac{crystal}{16} + \frac{crystal}{256} = 738078 \text{ Hz.}$$

The reason for employing this frequency is that the divide by 16 and the divide by 256 signals are already present on the existing CWRH system. So a chiprate of 738.0789 kHz, is selected for the chip rate. It is derived from the crystal reference as shown, results in a transmit bandwidth of 1.47 MHz, and resolves to approximately 25 % of the carrier cycle.

With the chip rate established, the appropriate length of the PN code can be determined. The code must be of sufficient length to ensure an unambiguous code phase at the receiver. If the staggered multiplexing technique proposed earlier is adopted, the amount of stagger, measured as code phase, must be large enough to ensure no ambiguity. This is accomplished by having the time of the staggered section longer than the propagation delay of the operating range of the system. The desired operating range for the hybrid system, is set to 50 km as described earlier. To ensure unambiguous code for this range, the minimum stagger length should have a duration of 166.67 μsec. This translates to 123 chips at a chip rate of 738.078 kHz selected earlier. From the desired specification of the hybrid system, for a total of 8 beacons in the system, a code length of 984 chips would have to be chosen to accommodate this stagger length of 123 chips in one code cycle. Since the PN code is generated using digital techniques the number of chips in a code are based on $2^n - 1$, where n is number of stages in the shift register. Therefore using 10 stages would result in a code being 1023 ($2^{10}-1$) chips long.

### *3.2.1.2 Type of PN code Sequence*

The type of PN code to be selected for the system depends upon the type of multiplexing technique used. The staggered technique proposed in section 3.1 is a compromise between the TDM and the CDM techniques. The TDM method is the simplest to implement. The CDM method and the staggered method proposed for the hybrid, where more than one beacon transmits at any given time, requires the code to be selected more carefully. Before a code is selected different properties of the code, such as the auto-correlation and the cross-correlation will be investigated.

The measurement of how well the PN codes match is termed as the degree of correlation. This is given by number of bits of agreement minus the number of bits of disagreement for one code length. This degree of correlation is a value that is obtained for the given pair of codes and their phase. Figure 3.4 shows how correlation value is achieved for two binary sequences. The plot of such correlation values over all the phases of the code would result in a correlation function of the code.

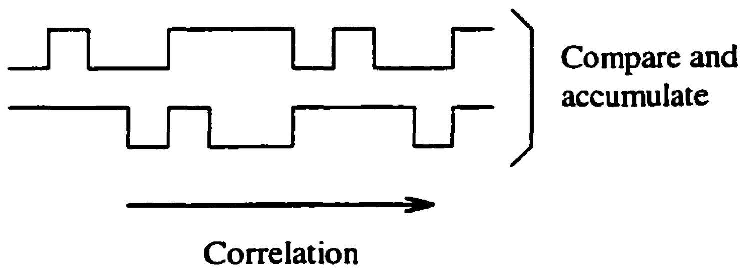



Figure 3.4 Correlation

The correlation function of a code when compared to itself is maximum only at zero phase shift. This maximum value is equal to the number of bits in the code. This correlation function is known as the auto-correlation of a code. The correlation function of a code when compared to a different code (with all the phase shifts) results in a plot of correlation values which is a function similar to the autocorrelation function except that the maximum values of the cross-correlation function is always below the maximum values of the auto-correlation function.

Figure 3.5 shows the a typical cross-correlation and auto-correlation function of a code. It is seen that the inphase correlation value is the largest and is greater than any other correlation value.

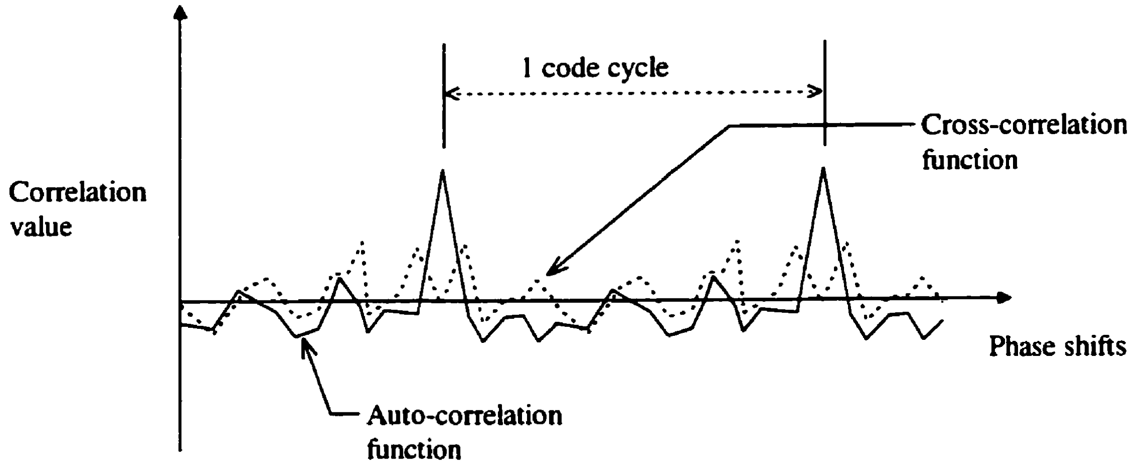



Figure 3.5 Correlation functions of a Gold code

When selecting the PN code for a CDM system, it is desirable to have the maximum margin between the maximum autocorrelation value and all other values. This would maximize the receiver's ability to synchronize only to the desired code. The Gold code is a commonly used PN code selected for CDM. The Gold codes, have a good deterministic cross-correlation which is significantly lower than the maximum autocorrelation value. However the auto-correlation for a Gold code is not a minimum and constant in magnitude for all the phase shifts of the code as compared to a maximal sequence. GPS is a typical example of a spread spectrum ranging system which employs Gold code as the system's PN code. The other advantage of the Gold code is that a large number of Gold codes can be generated for a given generator hence opening the possibility of a large number of transmitters operating in the same channel. Therefore a CDM system identifies each transmitter by the code it receives.

The code required for the staggered multiplexing technique proposed for the hybrid system, does not have to be unique for each beacon since the different beacons are identified by the time they transmit with respect to the master transmission time. Since only one code is employed the auto-correlation function of the code should have the largest margin between inphase and out-of-phase correlation values. The code selected should also be such that the phase of the code can be offset easily. This would enable the mobile to switch from one beacon transmission to another for fast acquisition and synchronizing during range measurement. These requirements of unique auto-correlation and the ability to shift phase are the properties of a maximal linear code sequence often called as the *m-sequences* or the *PN-codes*.

By definition, maximal code sequences are the longest codes that can be generated by a binary shift register of a given length. If $n$ is the number of stages in a sequence generator the maximal length sequence is $2^n - 1$ chips long. The shift register sequence generator consists of a shift register with feedback of a logical combination of two or more stages fed to the input. This feedback logical combination is most commonly a modulo two adder. Figure 3.6 shows general maximal sequence generator.

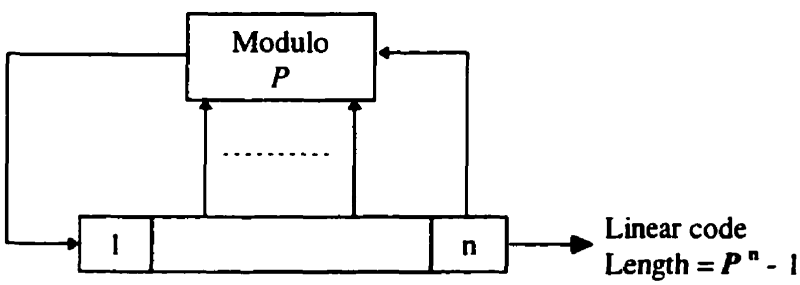



Figure 3.6 Linear Code Generator for P-ary Shift Register

One of the important properties of a maximal sequence is that the autocorrelation values for the sequence are such that for all values of phase shift, the correlation value is -1, except for the $0 \pm 1$ chip phase shift area. The autocorrelation function of a linear maximal sequence is as shown in Figure 3.7

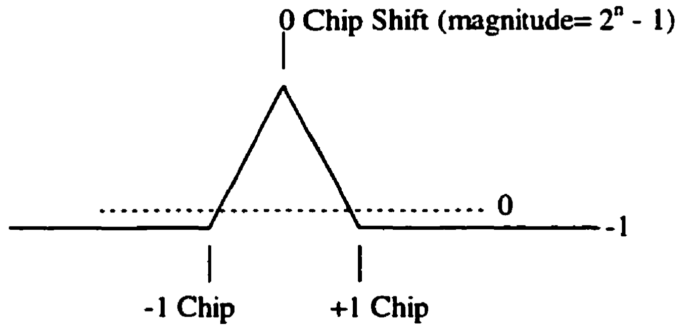



Figure 3.7 Autocorrelation of a maximal sequence

Crosscorrelation of the code is another property of the PN code which should be considered when using CDM. Crosscorrelation of maximal sequences are undeterministic and very poor. However since the hybrid system is not intended to be used with other codes, the crosscorrelation property is irrelevant.

There are other interesting properties of m-sequence codes which upon adding two similar length sequences of different phases, results in a non maximal linear sequence. This property is utilized by the GPS which uses a Gold Code[16]. Gold codes provide a compromise between the high autocorrelation and the low crosscorrelation of the maximal linear sequence. This is especially attractive for military applications where signal jamming and detection is a major concern.

*3.2.1.3 System Timing*

After knowing the chip rate and the length of the PN code to be used in the hybrid system the proposal for staggered code for time division multiplexing becomes clearer. The selected code ensures that only one code can be used by the whole system. The unique auto-correlation of the code along with the staggered transmissions would have a unique correlation function for each transmitter at the receiver. The amount of staggering depends on the operating range of the system. It was determined that for a maximum operating range of 50 km the stagger length required would be 128 chips at a chiprate of 738 kHz. This is the minimum stagger time required between different transmissions.

The hybrid system is intended to operate in a local area, this introduces another problem known as the near-far problem. The near-far problem occurs when transmitters are located in a local area. The receiver when operating close to a transmitter can be jammed by this nearby transmitter while trying to receive from a more distant transmitter. The figure below shows a typical situation of a near-far problem.

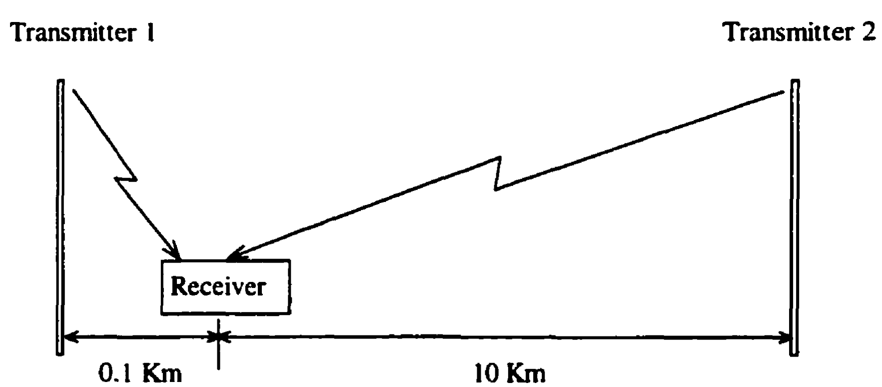



Figure 3.8 Near-far effect in a local area spread spectrum system

For a typical CDM system this is a common problem, when all the transmitters are transmitting simultaneously. The range within which a receiver can operate near the vicinity of a transmitter without being jammed is determined by the jamming margin of the receiver. For example, if the ratio of distances to a receiver from two transmitters is 100 then the difference in signal level arriving at the receiver is $100^2$, assuming square law propagation[22]. The signal arriving from the closer transmitter is 10,000 times stronger than the other transmitter. If the receiver is trying to receive from the distant transmitter than it experiences a jamming to signal ratio of 40 dB from the nearby transmitter. For the receiver to operate satisfactorily in the above condition it would require a jamming margin of 40 dB.

Jamming margin is defined as the process gain minus the usable signal to noise ratio at the output of the receiver[8]. According to FCC part 15, a receiver should have at least 10 dB S/N at the output for a 0 dB S/N at the input. This means that the receiver has to produce an output signal which has 10 dB S/N or greater for any received signal. If the receiver has a processing gain then the receiver can interpret an input signal which has a negative S/N. For example if the receiver has a processing gain of 15 dB then an input signal of -5 dB S/N can be used to produce a usable output. A receiver that operates or is capable of operating with a negative S/N ratio at the input is said to have a jamming margin. In the above example the receiver has a jamming margin of 5 dB.

The near-far problem in the direct sequence system used in a local area, is an example of jamming. The nearby transmitter causes jamming when the receiver is receiving from the distant transmitter. The jamming margin of the receiver determines the range from a transmitter it can operate and successfully measure range from other beacons. The most common solution is using some form of TDM [22]. However since the proposed timing method for the hybrid system uses staggered transmissions the effect of jamming is reduced only by the period of simultaneous transmissions of two adjacent beacons. This effect of stagger length can be investigated to determine the range of operation near the vicinity of a transmitter. The method for staggering was suggested for an increase in the rate of range measurements as compared to a complete TDM technique. An investigation of different stagger lengths will also reflect on the number of range measurements performed per second.

To determine the jamming margin of the hybrid system let us consider the worst case where no staggering is used. The process gain of the hybrid system is given by $T/T_c$; where T is the code length and $T_c$ is the chip length; which is N or number of chips in the code. This gives the hybrid system a process gain of 30 dB for a 1023 chip long code. Assuming the receiver complies with the FCC and DOC regulation, which requires it have a usable S/N of 10 dB, the receiver can operate with a signal input of -20 dB. For the near-far problem the ratio of the signal levels arriving at the receiver is the square of the ratio of the distances from the transmitters (assuming square law propagation). The jamming signal transmitted by the near transmitter is $10 * \log(\text{ratio})^2$ dB larger than the far transmitter. For the hybrid system having a jamming margin of 20 dB (J/S jamming to signal ratio), the ratio of the distances to the receiver from the two transmitters can be determined.

$10 \log \{ (\text{ratio})^2 \} = 20$ dB $\therefore$ ratio = 10 ; which is the ratio of distance from the two transmitters at the receiver. If the distance between the transmitters is assumed as 10 km, then the minimum distance the receiver can be near a transmitter is 1000 meters. This range from a transmitter is considerable and makes a local area system limited. The near-far problem can be completely avoided if strictly TDM is employed as a multiplexing technique and not more than one transmitter is operating at any given time.

The near-far problem also exists for the staggered technique, however the portion of the code and the duration of the time when only one beacon is transmitting is not affected by this problem. The staggering however allows only part of the code to be jammed by the near transmitter. This partial jamming allows the receiver to operate near a transmitter with an effective decrease in the receiver's process gain. For example, if there was no jamming the beacon's carrier phase is measured over one code length. This one full code length is seen as the data rate in the calculation of process gain for the receiver. However in the staggered method, if the receiver's output is totally unusable during the jammed portion of the code, the part of the code which is not overlapping becomes usable. This usable time when the carrier phase can be measured can be seen as the new data rate. This new data rate is higher than the original data rate, which causes a decrease in process gain near the transmitter. For a stagger length of 1/8th code or 127 chips the process gain reduces from 30 dB to 21 dB. Therefore if the hybrid system can operate with a processing gain of 20 dB the system can be usable even when close to a transmitter. Another technique which can be employed with the staggered method is that if the stagger length is such that only two other beacons are affected then the effect of the near far problem can be reduced. The beacons can also be strategically placed so that the mobile does not necessarily require range information from the jammed beacons.

The number of range measurements per second can be calculated for the stagger length of 1/8th of the code cycle. A total of 8 beacons are considered in the system. The whole modulation cycle for all the beacons and the master to transmit takes 3 code lengths or 4.15 msec. Assuming the receiver can measure phase from all the beacons and the master during this modulation cycle, a total of 240 measurements can be achieved for 1 second. Table 3.2 shows the effect of different stagger lengths for the proposed multiplexing technique.

Table 3.2 Comparison of different stagger lengths in the near field

| Stagger Length | 1/8 | 1/4 | 1/2 | 3/4 | 1 |
|---|---|---|---|---|---|
| Effective process gain (dB) | 21 | 24 | 27 | 28.8 | 30 |
| Number of beacons affected | 7 | 6 | 2 | 2 | 0 |
| Modulation cycle time(code lengths) | 3 | 4.25 | 6.5 | 8.75 | 10 |
| Range measurements per second | 240 | 169 | 110 | 82 | 72 |

Figure 3.9 shows the staggered multiplexing technique for the different lengths in the above table. The modulation cycle time indicates the number of range updates a system can possibly obtain.

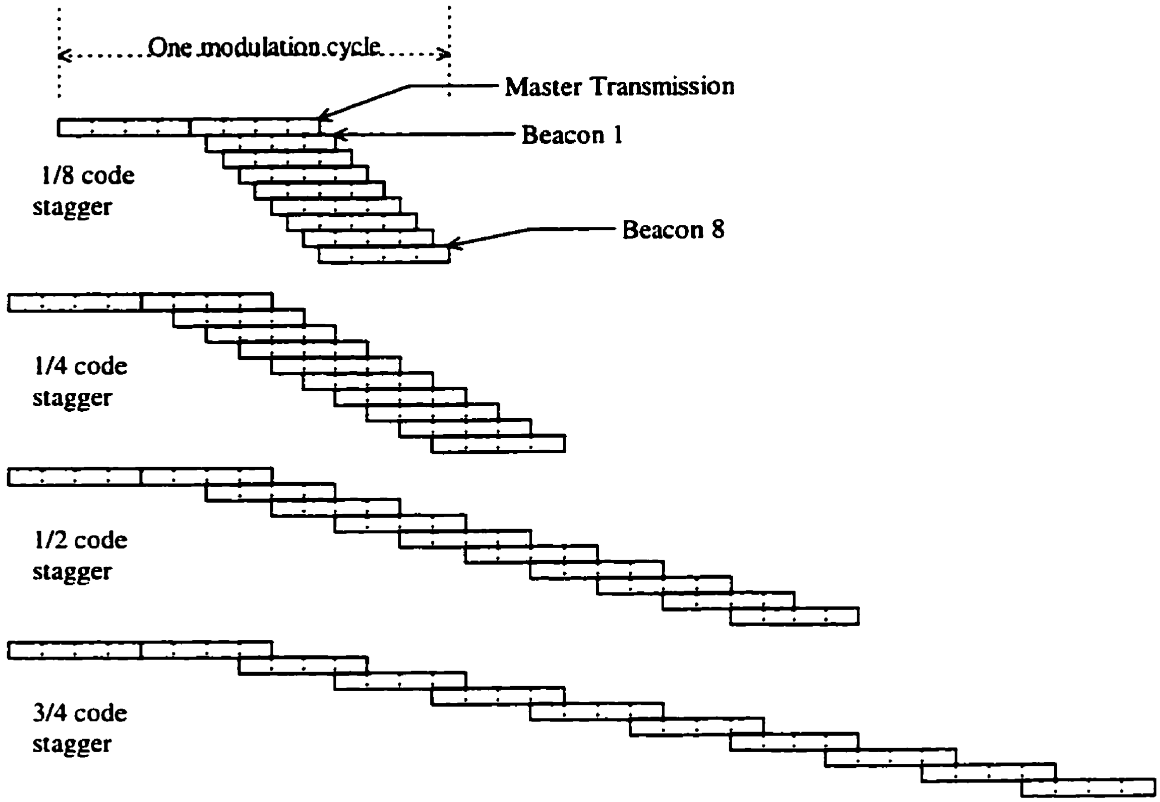



Figure 3.9 Multiplexing for different stagger lengths

As seen from Table 3.2 although staggering provides an increase in the available range measurements per second, the effect of near far problem is still present. The applications for which the hybrid system is proposed; namely farming, mining etc., do not require high data rates. However these applications require the system to be operational near the transmitters. This requirement makes it important to consider the option of having a stagger length of one full code length ; i.e. full TDM. The number of range measurements per second for full TDM is still 72, which is still considerably higher than the desired rate in Table 3.1. The other advantage is the process gain of the system is constant over the entire operating area. Therefore a modulation scheme with full TDM and no staggering is best suited for the proposed hybrid system.

### *3.2.1.4 PN Code Generator*

The PN code generator can be made of any set of delay elements or shift registers. The number of shift registers determine the length of the code generated. To generate a 1023 bit long PN code the shift register has to be ten bits long, i.e. $2^{10} - 1 = 1023$.

Determination of the feedback taps for the generator is the next design detail. Convenient tables have been developed for the feedback connections[30] which yield maximal sequences. For a PN code which is 1023 bits long, a 10 bit shift register is needed with feed back taps from the $10^{th}$ stage and the $3^{rd}$ stage.

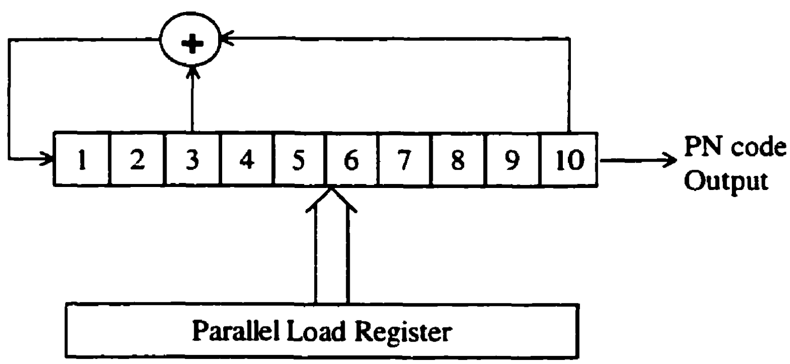



Figure 3.10 PN Code Generator Block Diagram

The code generator must have the capability of offsetting the current phase to 1/8th of the code cycle. This is required when measuring range from one beacon to another. The parallel load register enables the generator to start the code generator from any phase.

### 3.2.2 Bi-Phase Modulation

The PN code is used to modulate the carrier using phase shift keying. In a direct sequence system the carrier is modulated by phase shift keying at the code rate; that is for a "One" in the code pattern, one carrier phase(0 degree) is transmitted, and for a "Zero" a different carrier phase(180 degree) is transmitted. Direct sequence systems employ suppressed carrier transmission which requires that a balanced modulator be used.

A balanced modulator can be illustrated as a single pole double throw switch which has a carrier with zero phase shift connected to one contact and 180 degree phase shifted carrier connected to another. The modulating signal controls the pole of the switch. There are many commercially available balanced modulators / mixers, the most commonly used are the double balanced modulator / mixer.

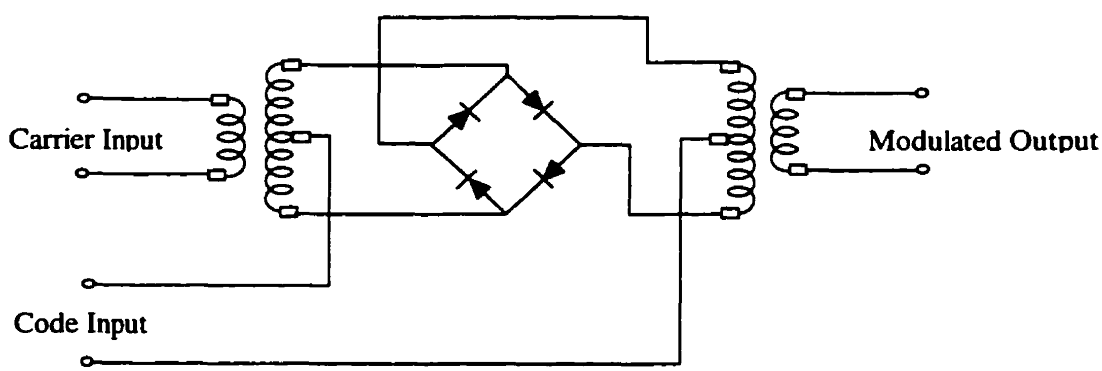



Figure 3.11 Double Balanced Modulator

The spectrum of a PN code modulated carrier is a set of symmetrical distributed sidebands having an envelope of $[(\sin x)/x]^2$ function. The sidebands which are randomly placed apart from each other due to the randomness in the modulating code.

The modulator that is used should provide good carrier and code suppression[23] to avoid narrow band interference and ease of delectability. There are readily available commercial components which performs the bi-phase modulation with excellent carrier and code suppression.

### 3.2.3 Despreading and Correlation

The spread carrier when received has to be de-spread to the original carrier. This process of recovering the original carrier is known as correlation, where a local replica of the code is multiplied with the received signal. This locally generated PN code must be synchronized to the incoming PN code spread carrier to completely recover the carrier. In other words, if the transmitter code and the receiver code are time synchronized, then at each phase shift of the  of the received signal the receiver code reverses the phase. Figure 3.12 shows the carrier recovery performed by a correlator.

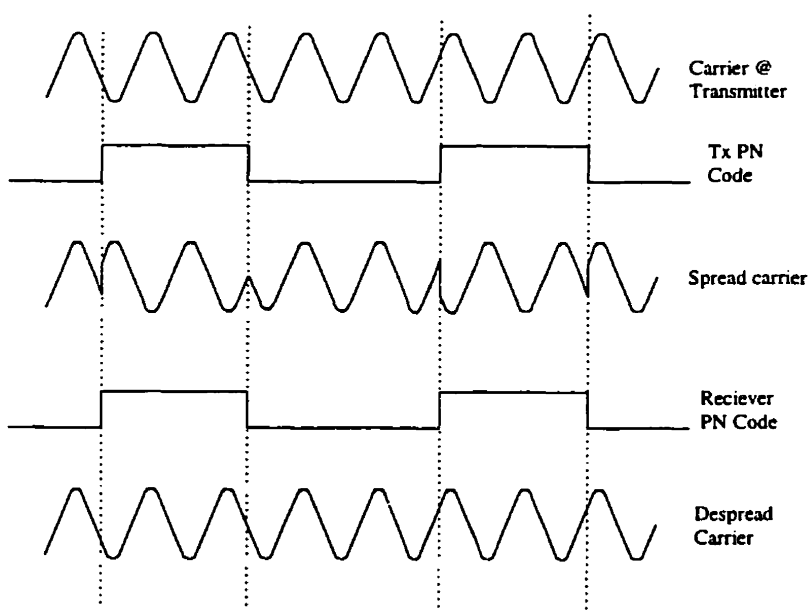



Figure 3.12 Carrier Spreading and Despreading

There are two basic types of correlators: the "in-line" and the "heterodyne". The in-line correlator provides the simplest method of de-spreading the received PSK signal. In this method the local reference PN code is fed to one of the inputs of a balanced modulator, and the received signal is fed to the other input of the modulator. The in-line correlator, although simple, has very little practical application. Heterodyne correlators are the most common types used for practical applications because the de-spread output can be shifted to a lower frequency. This process of shifting the de-spread carrier to a lower frequency simplifies the receiver design. In a heterodyne correlator a similar double balanced mixer as used in the transmitter is used for correlation. The de-spreading of the signal is done by frequency-by-frequency multiplication of the local reference, or can also be viewed as chip-by-chip code comparison in the time domain. The received signal consists of sidebands that are related to the PN code. The local reference sidebands correspond frequency-by-frequency to the received signal sidebands when the local PN code is synchronized. This correspondence permits correlation and production of a despread output.

### 3.2.4 Synchronization

The discussion in section 3.2.3 is based on the assumption that the receiver PN code is synchronized to the transmitter code. Synchronization cannot be assumed; it must be achieved. The carrier frequency and the code phase at the receiver are the two general uncertainties which exist in most spread spectrum systems. The code rate and the amount of Doppler frequency effect also contribute to the general uncertainty.

The carrier frequency as seen at the receiver should be resolved so that it falls within the bandwidth of the post correlation filter. The code generation of the system can be designed such that the code rate and the carrier are derived from the same reference; this eliminates the problem for code rate uncertainty. Code phase resolution is the most prominent problem for any spread spectrum system.

The next uncertainty is the code phase at the receiver. The receiver PN code should be resolved to better than one chip to detect the presence of the transmitted spread carrier. To achieve this, the receiver code phase should be varied and the intermediate frequency output should be observed to detect the carrier and the degree of correlation.

#### *3.2.4.1 Synchronization Detector*

The synchronization of the receiver code to that of the transmitter is achieved by delaying either the incoming signal or by shifting the local PN code. The proposed hybrid system proposed employs the latter technique of offsetting the local receiver PN code and observing the output at the IF(intermediate frequency) stage. The correlator output is a perfect carrier (with baseband modulation if carrier was baseband modulated), when the receiver PN code is perfectly synchronized to that of the transmitter. A typical direct sequence synchronization block diagram is as shown in Figure 3.13

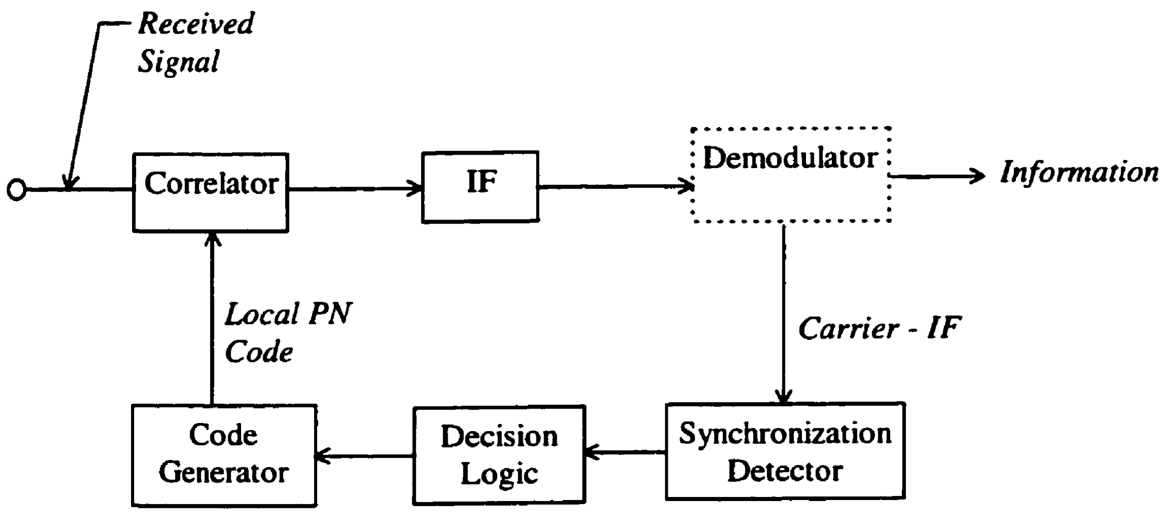



Figure 3.13 Typical Direct Sequence Synchronization Recognition Block Diagram

The hybrid system's the synchronization section is as shown in Figure 3.14. The main difference between the typical synchronization recognition and that of the hybrid system is that of the demodulator. The function of the decision logic is handled by the system's microprocessor.

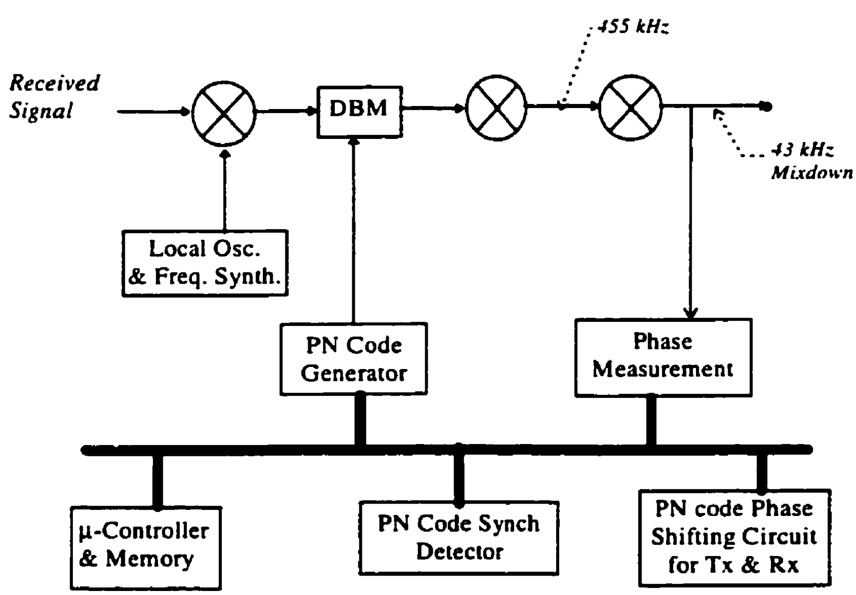



Figure 3.14 Hybrid system Synchronization Block Diagram

The basic synchronization detector consists of an envelope detector followed by an integrator. The output level of the integrator determines the level of the synchronization or how close the two codes are matched. This output is then fed to a schmitt trigger level detection circuit. The low trigger point of this circuit should be above the crosscorrelation level of the system to avoid a false trigger. For the hybrid system there are different methods available to achieve synchronization detection. The selection of a particular method would depend upon the synchronization acquisition times.

The FM receiver chip used in the system manufactured by Motorola Inc. MC3362 has a RSSI circuit which with the help of an external circuit would generate a voltage proportional to the signal strength [24]. This voltage can be fed into the microprocessor's built-in analog to digital converter.

The IF of 455 kHz can also be used to detect synchronization by using an envelope detector and the output of the envelope detector can be fed to the A/D converter to do the integration and the decision logic of Figure 3.13.

Another method to recognize synchronization is by digitizing the 455 kHz IF using an external high resolution A/D to detect the agreements and disagreements in the time domain to achieve correlation.

Although different methods are suggested to achieve synchronization the final decision lies with a satisfactory synchronization acquisition time. The usual trade-off between hardware and software should also be considered. The next process for synchronizing the local PN code is shifting the phase of the code.

### *3.2.4.2 Code Sliding and Phase offsetting*

The synchronization detector gives the error signal which is proportional to the amount of offset required for the local PN code to be synchronized with the received signal. The hybrid system employs two levels of shifting: coarse sliding and the fine sliding.Coarse sliding of the PN code is used for the initial synchronization, which is achieved by the chip insertor /deletor. The chip insertor and deletor circuit inserts the positive edge of the PN code clock to occur half a chip earlier or half a chip later. This enables the PN code phase to jump and slide half a chip at a time. Figure 3.15 shows the chip insertion and deletion of the PN code clock.

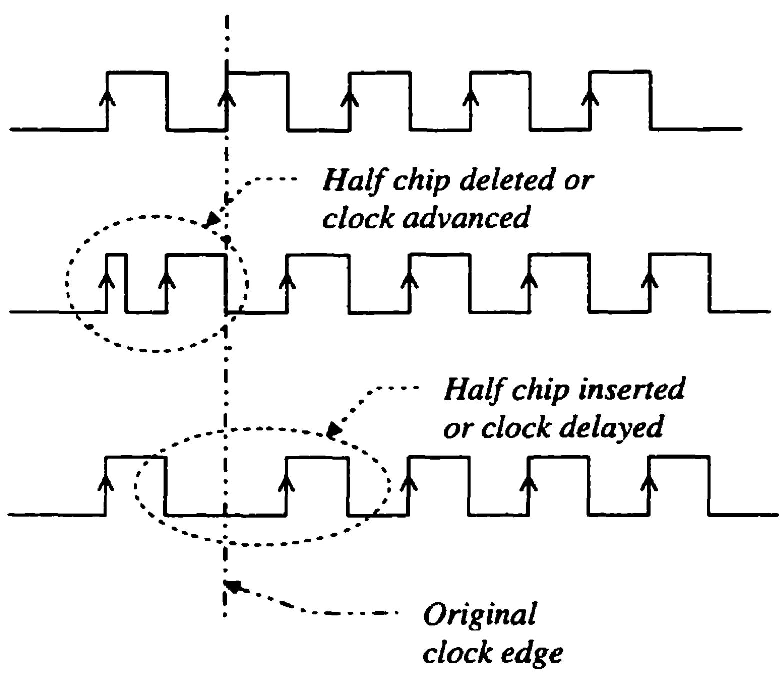



Figure 3.15 Chip insertion and deletion.

Once the local PN code is within half a chip of full synchronization the fine sliding circuit should bring the code to full synchronization with the received signal. This is achieved by a phase locked loop as shown in Figure 3.16. This technique is derived from the transmit section of the current CWRH system, where the phase of the carrier can be offset to any 1/256 part of the cycle.

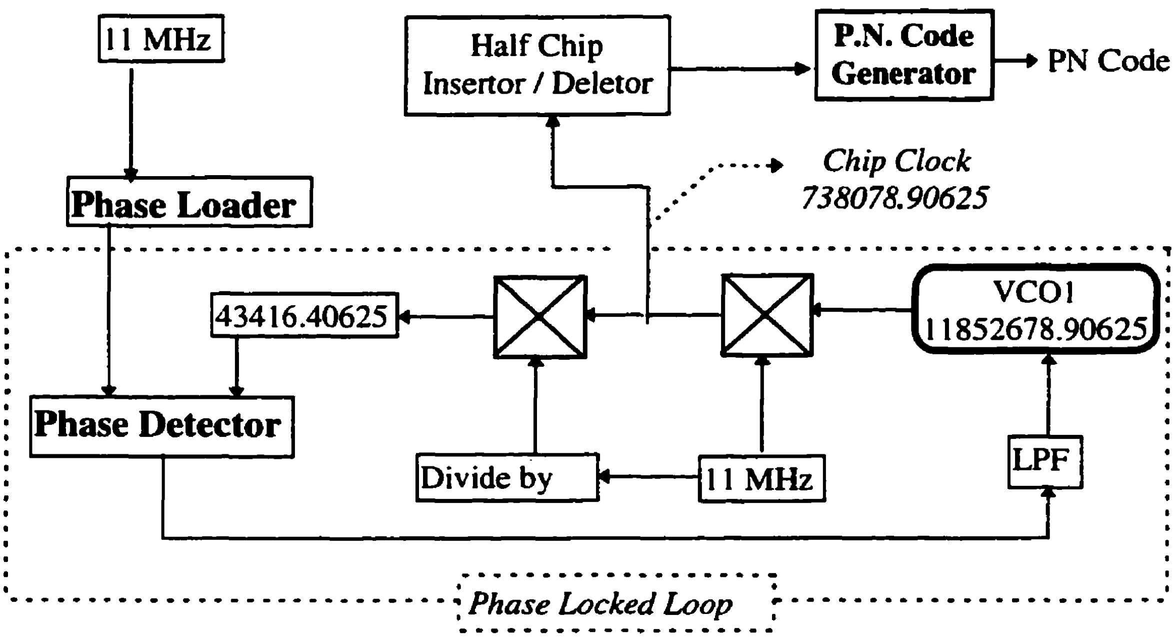



Figure 3.16 PN Code Phase Sliding block diagram.

The PN code clock is derived from a voltage controlled oscillator which is coherent to the reference 11 MHz crystal oscillator. The phase locked loop indicated by the dotted box also has a reference frequency which is derived from the 11 MHz oscillator. The phase of this reference determines the phase of the VCO which in turn determines the phase of the PN code clock. The resolution of the phase offsetting circuit is of 8 bits or 256 steps. This enables shifting the phase of the reference signal of the PLL which is at 43 kHz in $1/256^{th}$ degree steps, which in turn would shift the phase of the PN code clock with the same resolution. This process of shifting the phase using a PLL is already utilized in the existing system to offset the phase of the continuous wave carrier. This process permits the hybrid system to slide the PN code fine enough to synchronize the local PN code to within less than half of the carrier cycle. The PLL is implemented completely in a FPGA except for the VCO. The mixers shown are digital mixers using a simple D-Flip Flop[25], [ Appendix A].

### 3.2.5 Fast TX / RX Switching for TDM

Since the hybrid system is a time division multiplexed system and the transmission and the reception is done through the same antenna and at the same frequency, care should be taken to avoid interference from the transmit section when the receive section is turned on. The CWRH system solves this problem by turning the transmit oscillator off during reception and on while transmitting. This solution requires the phase locked loop for the carrier in the transmit section to lose lock and cause an additional delay during the start of each transmission. An alternate method is proposed to eliminate this delay during transmission without having the transmit section interfere during the receive mode.

The CWRH system disables the transmit VCO by shutting the power off and restarting every time the transmitter is turned on. This causes extra delay or lock time for the transmit section to produce a stable carrier. The transmit VCO is disabled so that no on board signals are present within the bandwidth of the receiver. This can also be achieved by tuning the transmit PLL out of the receiver range. The alternate method proposed is to design a PLL producing a signal that is far away in frequency from the system's carrier. This signal is then used in conjunction with another signal to produce the system's carrier. In the hybrid system a PLL generating a 55 MHz signal is kept in constant lock which, upon mixing with 11 MHz signal, produces 66 MHz (sum) and the 44 MHz (difference) signals. The sum of the two frequencies can be easily filtered out, which leaves the difference which is the carrier frequency. During the switch from the transmit to receive mode the input to the mixers can be cut off thereby eliminating the chance of producing the carrier signal. The main advantage of this method is that there is no initial startup delay to lock the PLL since the 55 MHz loop is already locked. The only delay is in the closing of the switches at the input of the mixer. Figure 3.17 shows the block diagram of the proposed technique.

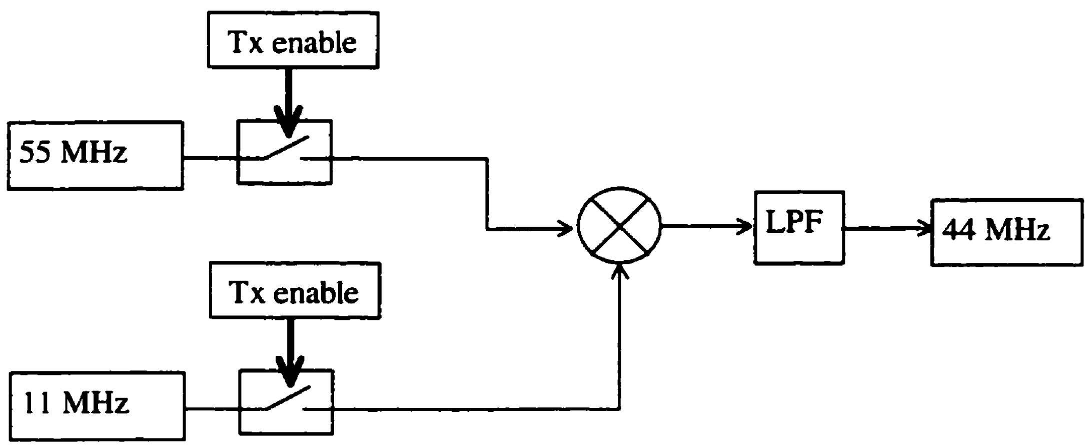



Figure 3.17 Fast Tx /Rx switch

### 3.2.6 Proposed System Components

Analysis of the additional functions of the hybrid system (PN code generation, modulation, synchronization and fast Tx/RX switching) has provided the basis for choosing the components required. PN code generation was determined by the chip rate, length and the type of the code required. The discussion on the modulation determined the type of modulator and the type of synchronization detector the hybrid system should use. The discussion on synchronization focused on the receivers used in the mobiles and beacons.

The detailed block diagram of the receive section of the hybrid system is shown in Figure 3.18. This block diagram portrays the section common to the mobile and beacons, which receives the spread signal, despreads, synchronizes and measures the phase of the carrier. The blocks enclosed in the shaded areas indicate the analog components in the system. The rest of the blocks can be implemented in a FPGA(Field Programmable Gate Array). The phase reader, the phase loader, the chip insertor/deletor and the code generator are interfaced to the microprocessor bus to read the phase of the carrier, load the phase of the PN code (1/256th of a chip), to advance or retard the clock to the code generator by half a chip and to load a phase offset of the PN code directly to the PN code generator. Therefore the external components required to convert the existing CWRH system to the hybrid system is limited to the external double balanced mixer and the Chip clock VCO(each for the transmit and receive section). The VCO is chosen at a frequency which is coherent to the reference 11 MHz clock.

The transmit section of the hybrid system performs the following functions: generation of the carrier, generation of the PN code and spreading of the PN code. These functions are common to the beacon and the master. Figure 3.19(a) shows the block diagram of the PLL for the generation of the 55 MHz signal from which the carrier is derived. Figure 3.19(b) shows the block diagram for the generation and spreading of the carrier. Figure 3.20 shows the block diagram for the generation of the chip clock. The VCO utilized in the transmit chip clock generation is coherent to the 11 MHz reference oscillator and at a different frequency from that of receive chip clock VCO to avoid any mutual interference with the PLL circuit.

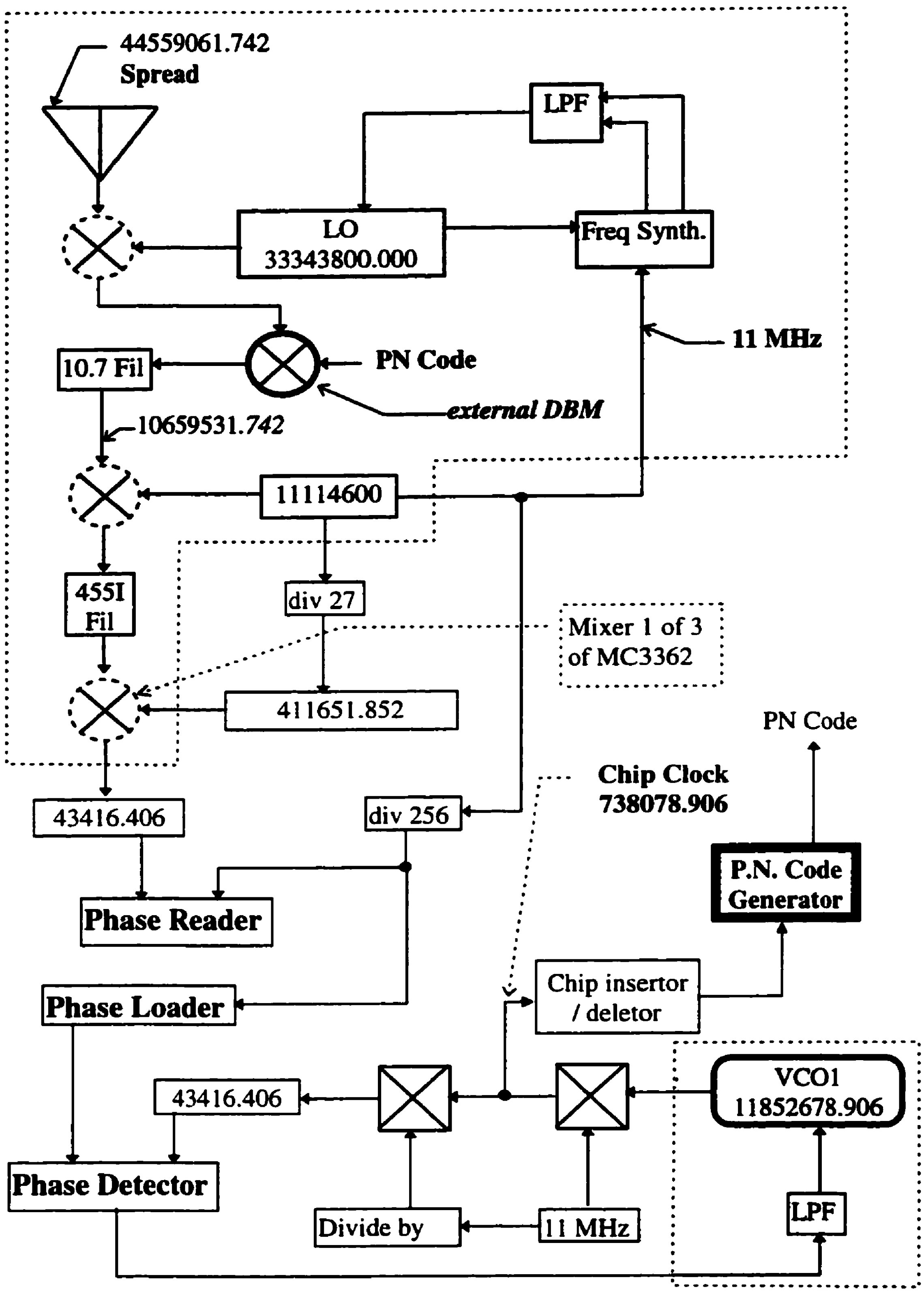
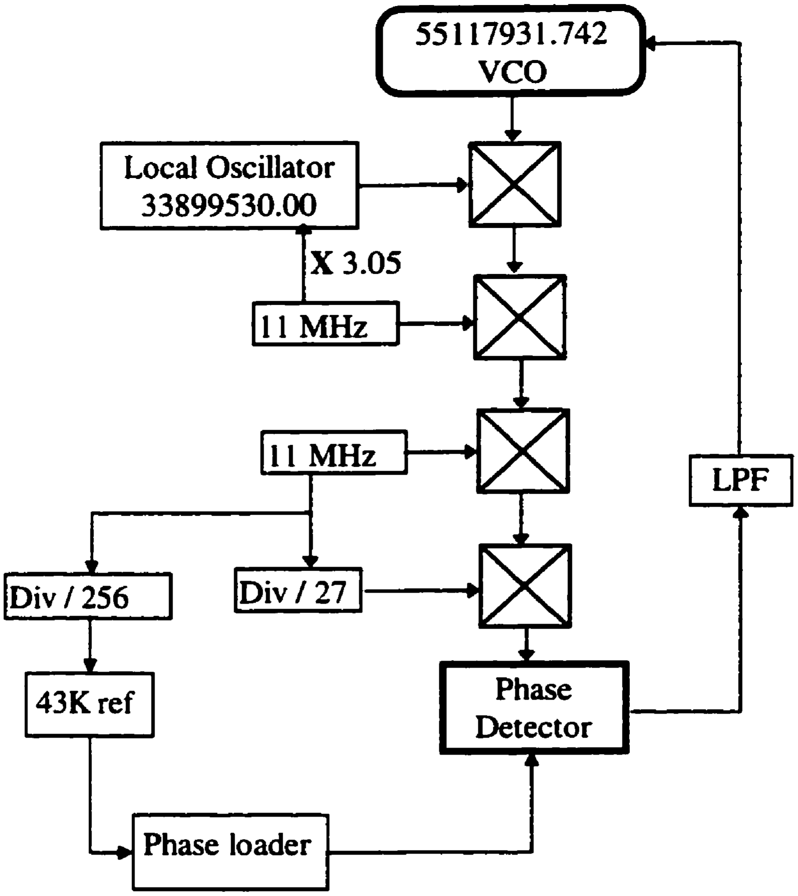
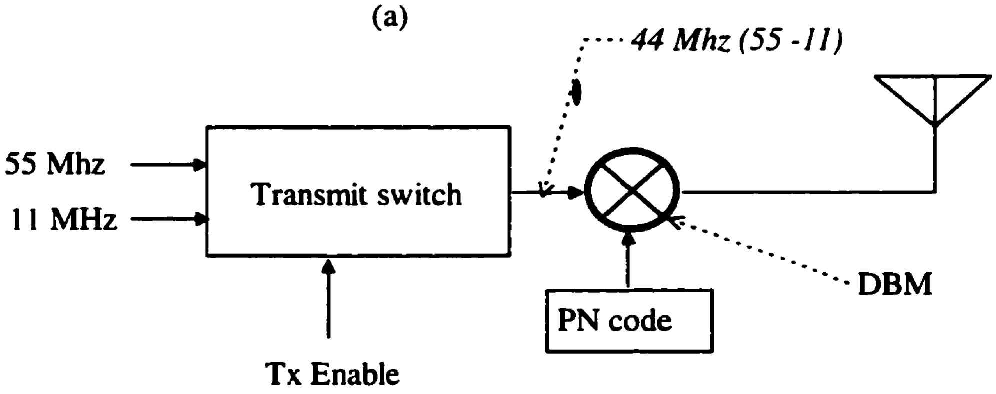



Figure 3.18 Hybrid System Receiver.




(a)




(b)

Figure 3.19 Transmit Carrier Generation

(a)55 MHz PLL, (b) Transmit switch and carrier spreader

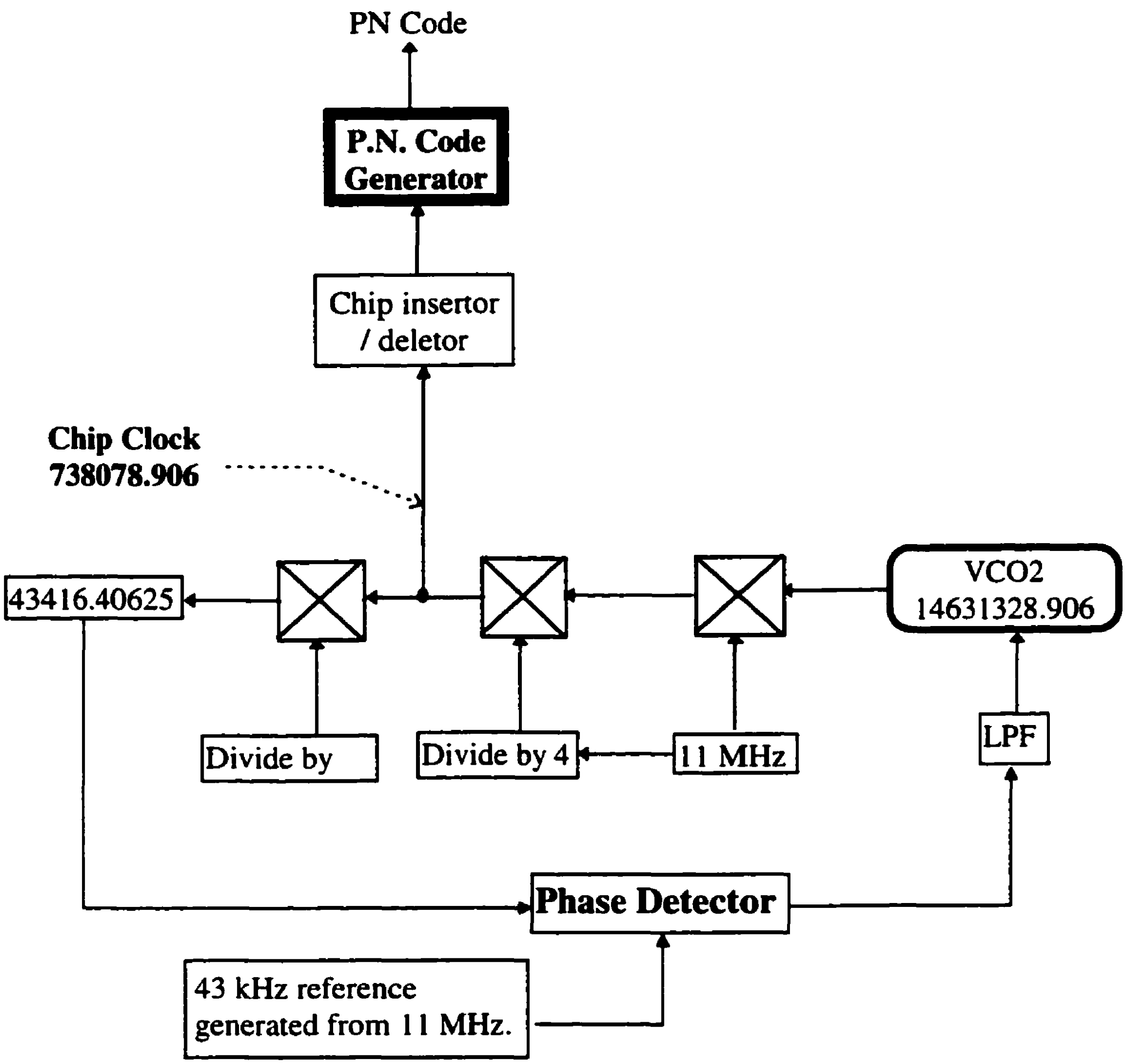



Figure 3.20 Transmit Chip Clock Generation

The PLL shown in Figure 3.19 is at 55 MHz which is not the carrier frequency. This is done to accommodate the Master and Beacon transponders to enable switching of the transmitter. This setup enables the 55 MHz PLL to be locked and stable before the carrier is used to transmit, which results in an easy design of the PLL for a phase step response. The transmit switch is implemented by using a digital mixer, with an output enable as shown in Figure 3.21.

| *Tx Enable* | *Output* |
| --- | --- |
| Enable | 55 Mhz - 11 Mhz |
| Disable | DC |

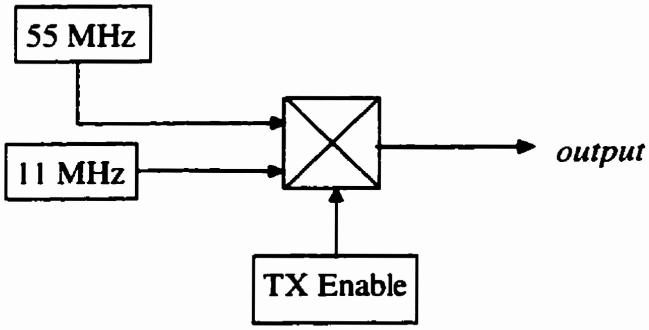



Figure 3.21 Transmit Enable Switch

The three components described in the proposed hybrid system are the DBM, PN code generator and the code sliding and offsetting circuit. Chapter 4 analyses and shows the simulation results of these components.

## Chapter 4

# 4. System Selection, Verification and Simulation

The proposed hybrid ranging system is based on the current CW system.

Figure 4.1 and Figure 4.2 show the block diagram of the transmit and the receive sections of the hybrid ranging system. The shaded areas indicate the additional components that are required for the hybrid system.

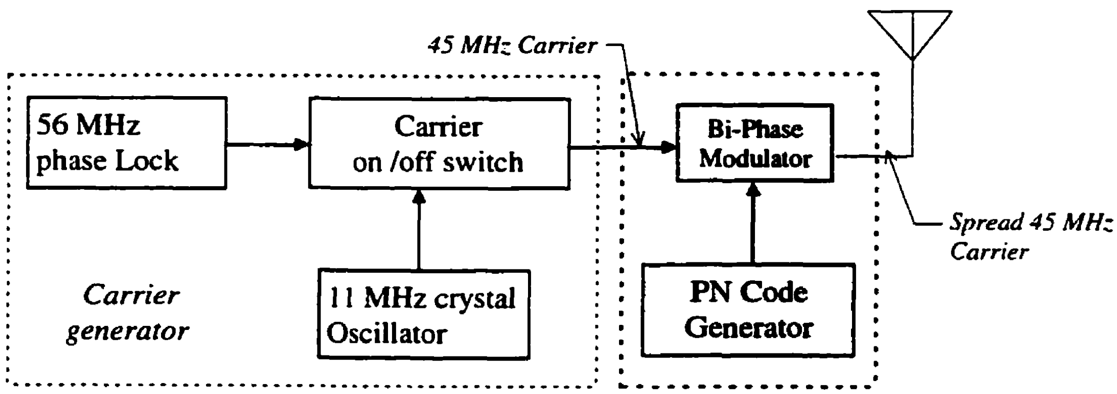



Figure 4.1 Transmit section of hybrid system

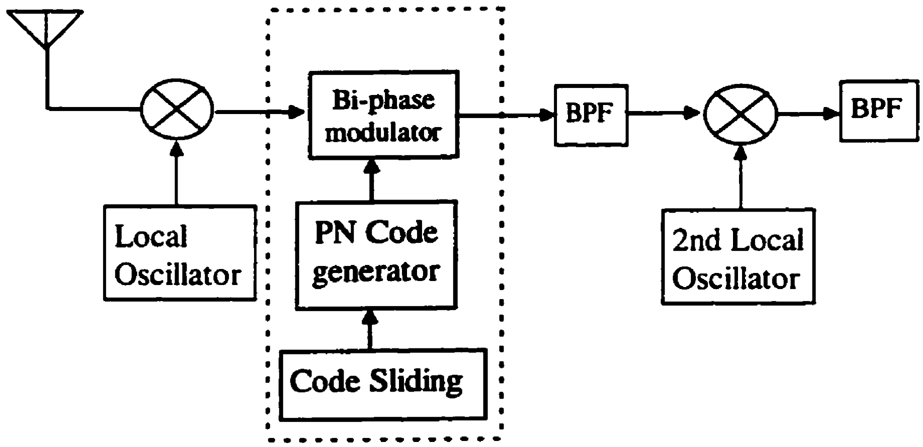



Figure 4.2 Hybrid system receive section.

The transmit section is used in the master and the beacons whereas the receive section is used in the beacon and the mobile. The transmit section will spread the carrier by modulating it with a PN code. The receive section will despread the carrier by using the same PN code as that used by the transmitter. The code generated by the receiver, needs to be shifted to be in synchronization with the transmit code. A code sliding circuit is required for shifting and synchronizing the local PN code to the received signal. The mobile requires only the receive section to measure the phase of the master and the beacons and therefore must be able to offset the phase of the local PN code to any desired phase.

Since the beacons in the proposed hybrid system and the original CWRH system use the same antenna for transmission and reception at the same frequency; the transmitter must be turned off during receiving. This requires a transmit-receive switch which will multiplex the antenna with the receiver and the transmitter.

This chapter analyses the main components that are required for the hybrid system, the double balanced modulator, the correlator, the code generator, the code phase slider and the transmit-receive switch used for multiplexing the antenna.

## 4.1 The double balanced modulator

The double balanced modulator is used in the transmitter to spread the carrier, and in the receiver to despread the carrier. The DBM shifts the carrier phase to 0 or 180 degrees. How well the DBM balances the amplitude and phase determines it's ability to suppress the carrier.

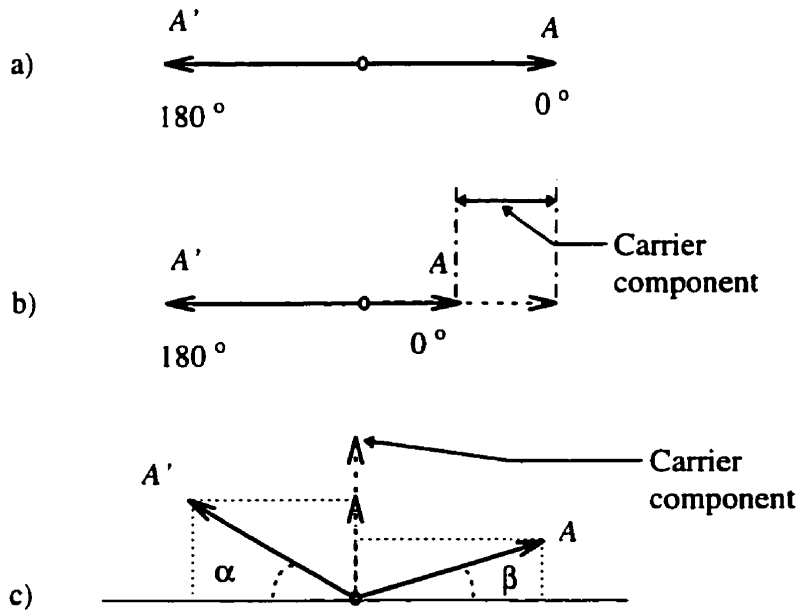



Figure 4.3 a) Ideal DBM ; b) Amplitude unbalance; c) Phase unbalance.[8]

Figure 4.3 shows a phasor diagram for the modulated output of the DBM. Part "a" is the output of an ideal DBM with no phase or amplitude unbalance. Part "b" and "c" are outputs where the amplitude and phase are unbalanced respectively. The carrier component present at the output of an amplitude unbalance DBM is the difference in amplitude of the two components. The carrier component for a phase unbalanced DBM is given by:

$$amplitude\ of\ carrier\ component = A'\ \sin\alpha + A\ \sin\beta$$

Where $A$ = amplitude of carrier at zero degree phase,

$A'$ = amplitude of carrier at 180 degree phase,

$\beta$ and $\alpha$ = A′ phase offset from $0^0$ and $180^0$ respectively.

If $B$ is the amplitude of desired sidebands, then carrier suppression can be expressed as,

$$V = 10 \quad \log \frac{B}{A'\sin\alpha \ + \ A\sin\beta} \quad dB$$

Ideally a double balanced modulator has a very high carrier suppression. From the specifications of commonly available DBMs it is apparent that the carrier suppression value ranges from 60 dB to 30 dB. Carrier suppression in a spread spectrum is important for the transmission as well as the reception. During transmission if the carrier is not suppressed, a narrow band of carrier signal is generated. This is not desirable for military applications where spread spectrum is used for undetectable transmission. In the case of the receiver the received signal is modulated by the PN code, this PN code spreads any narrow band signal present. However if the PN code is in synchronization with the received code then the signal is despread into a narrow band IF. If a narrow band signal is present at the carrier frequency or within the bandwidth of the IF filter, then a portion of this narrow band signal will be passed through the IF stage whose magnitude is equal to the carrier suppression of the mixer. This narrow band signal can falsely indicate to the synchronization detector the presence of a carrier, leading to a false lock.

There are many different types of balanced modulators that can be used for bi-phase modulation. The most common bi-phase modulators are intended for the frequency range of 900 MHz. The proposed system is at 45 MHz so a much lower frequency DBM will be required to achieve bi-phase modulation. A DBM with a fairly high carrier suppression can be chosen to achieve bi-phase modulation.

Two modulators were considered and their carrier suppression was noted. Firstly a common balanced modulator manufactured by Motorola, the MC1496, was purchased and tested. This is an integrated circuit based DBM. The other modulator was the SBL-1, manufactured by Mini Circuits Inc. The company produces passive DBMs which can be used for bi-phase modulation. The following figures show the different modulator's carrier suppression.

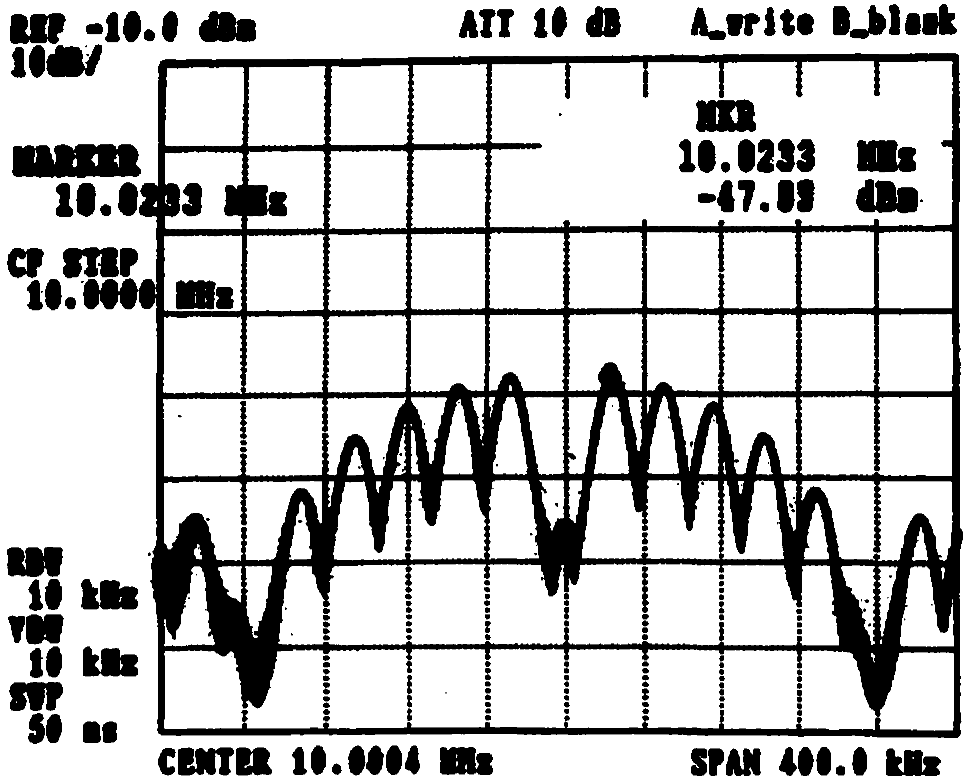



Figure 4.4 Carrier suppression of MC1496 ( Test carrier @ 10 MHz, span 400 kHz, Vertical scale 10 dBm /division)

Carrier suppression observed for MC1496 was approximately 19 dB. The test was performed with a 10 MHz carrier and a pulse generator used as the code generator. It was observed that the balanced modulator using this IC was sensitive to the signal levels and frequency appearing at the inputs[26]. An alternate test carried out with a hybrid balanced modulator shows a 10 dB improvement in carrier suppression. The other device used was the SBL-1 manufactured by Mini-Circuits Inc.[27]. The following figure shows the carrier suppression using the carrier at 44 MHz and the pulse generator adjusted to provide the bandwidth of the first sinx/x lobe of 1.4 MHz. This would represent an approximation to the proposed carrier frequency and chip rate.

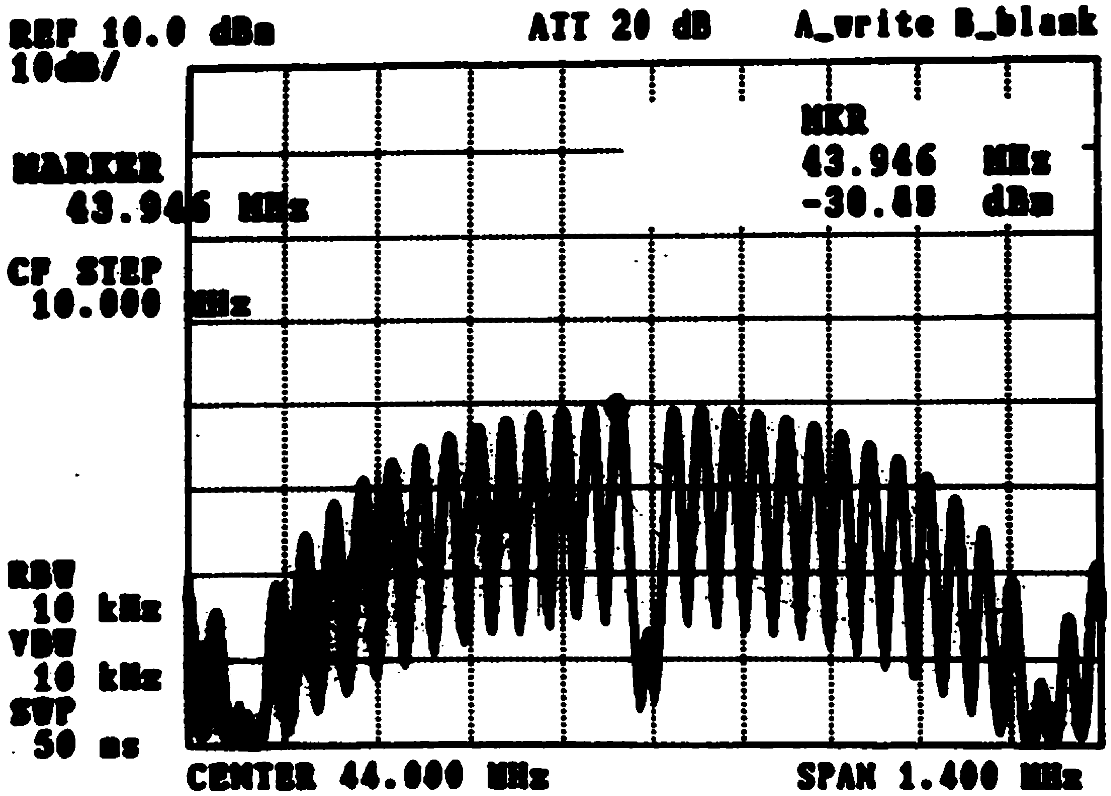



Figure 4.5 Carrier suppression of SBL-1 ( Test carrier @ 44 MHz, span 1.400 MHz, Vertical scale 10 dBm /division)

Comparing the two figures it can be seen that the SBL-1 has a better performance over the MC1496. The SBL-1 is a hybrid and did not require any additional components to perform the test. The carrier suppression achieved during the test for SBL-1 was 27dB as opposed to 15dB for the MC1496.

## 4.2 The correlator

A critical process of a Spread Spectrum receiver is correlation. Correlation is the measure of likeness of two signals. The correlator provides the degree of correlation between two signals. The design of a correlator consists of a multiplier followed by an integrator which produces the average correlation of the two signals over one PN code period.

In a Spread Spectrum receiver the PN code is the signal which must be correlated to the received PN code. The Spread Spectrum transmitter uses a carrier to transmit the PN code to the receiver, the receiver in turn uses the same PN code to extract the carrier. If the PN code at the receiver is in synchronization with the received signal a continuous carrier is extracted. However this synchronization can be achieved by using a correlator to measure the degree of synchronization.

Correlation is achieved by despreading or by bandwidth collapsing, the received spread signal followed by integration over one code cycle. The despreading is performed by a double balanced modulator/mixer(DBM) which does the multiplying part of the correlator. The DBM can be visualized as a device which produces a +1 when the level of both signals under consideration is of the same polarity, and produces -1 when of opposite polarity. In analog terms the DBM's output is a CW carrier signal when the PN code logic levels are the same and no average carrier when the PN code logic level is of opposite polarity. The integrator which follows the DBM gives the average output of the mixer which represents the average likeliness of the signal. Therefore if the carrier at the output of the DBM is present the same number of times as when the carrier is absent( -1), then the output of the integrator is zero, or no average carrier level is present for the integration period. This integration to be performed has to exactly cover one code length. This is necessary because the code employed usually has unique properties that identifies exact correlation over one code length. For example the code used in the hybrid system has a correlation output of -1 (one extra disagreed chip over the agreed chips). The technique of integrating and verifying the correlation of the code is also termed as acquisition. There are many methods suggested for acquisition [8].

The current CW ranging system utilizes an FM receiver integrated circuit (MC3362) which has two IF mixers. The IC also has an on chip received-signal-strength-indicator (RSSI) which is available as a current source, this indicates the strength of the carrier received. The meter drive circuitry detects the input signal level by monitoring the amount of limiting exerted on the limiting amplifier. The sensitivity of the RSSI indicator is linear over 60 dB, with the absolute being -110 dBm to -50 dBm. To use the RSSI as a correlator is questionable due to its unknown characteristics.

An alternate technique would be to design an integrator with a dump switch to refresh the integrator at the beginning and the end of the PN code cycle. This would give the exact level of correlation by detecting the presence of the IF. This would be the matched filter for the signal in question.

A digital approach would have the IF signal sampled and digitized. A Fourier analysis of the samples would yield the amplitude of the carrier component in the frequency domain. This technique has the advantage of yielding the phase of the carrier with respect to the local clock. Since this technique is the most suitable and would give an accurate representation of the correlation, it would be beneficial to use a DSP processor with a resolution corresponding to the dynamic range required for the hybrid system. The requirement of a fast A/D is not necessary because the IF can be mixed down to a low frequency.

## 4.3 Code Generator

The code used in the proposed system is a 1023 bit long linear maximal sequence. The choice of a simpler code as opposed to a more secure code such as the GOLD code is made for various reasons. The advantage of the Gold code is that it produces a very low cross-correlation and the ability to generate many different codes using the same generator. These advantages are very useful in applications where selectability and jamming is an issue, but in the proposed ranging system this is not of great importance. Maximal sequences have the property of ideal autocorrelation function which is of great interest in this application. The simplicity of the design of a maximal sequence generator allows the flexibility to shift the code to any desired phase which facilitates switching reception from one beacon to another. It is proposed here that a Maximal Sequence Code be used.

The design of the linear feedback shift register to obtain a maximal sequence code is readily available from pre-compiled tables. The feedback combination for the current design is selected for the minimum number of taps to minimize the routing delays in the FPGA. Figure 4.6 shows the design of one element of the code generator. The design is to be implemented so that phase offsetting of the code is easily possible. The following figures show the simulation results for the code generator.

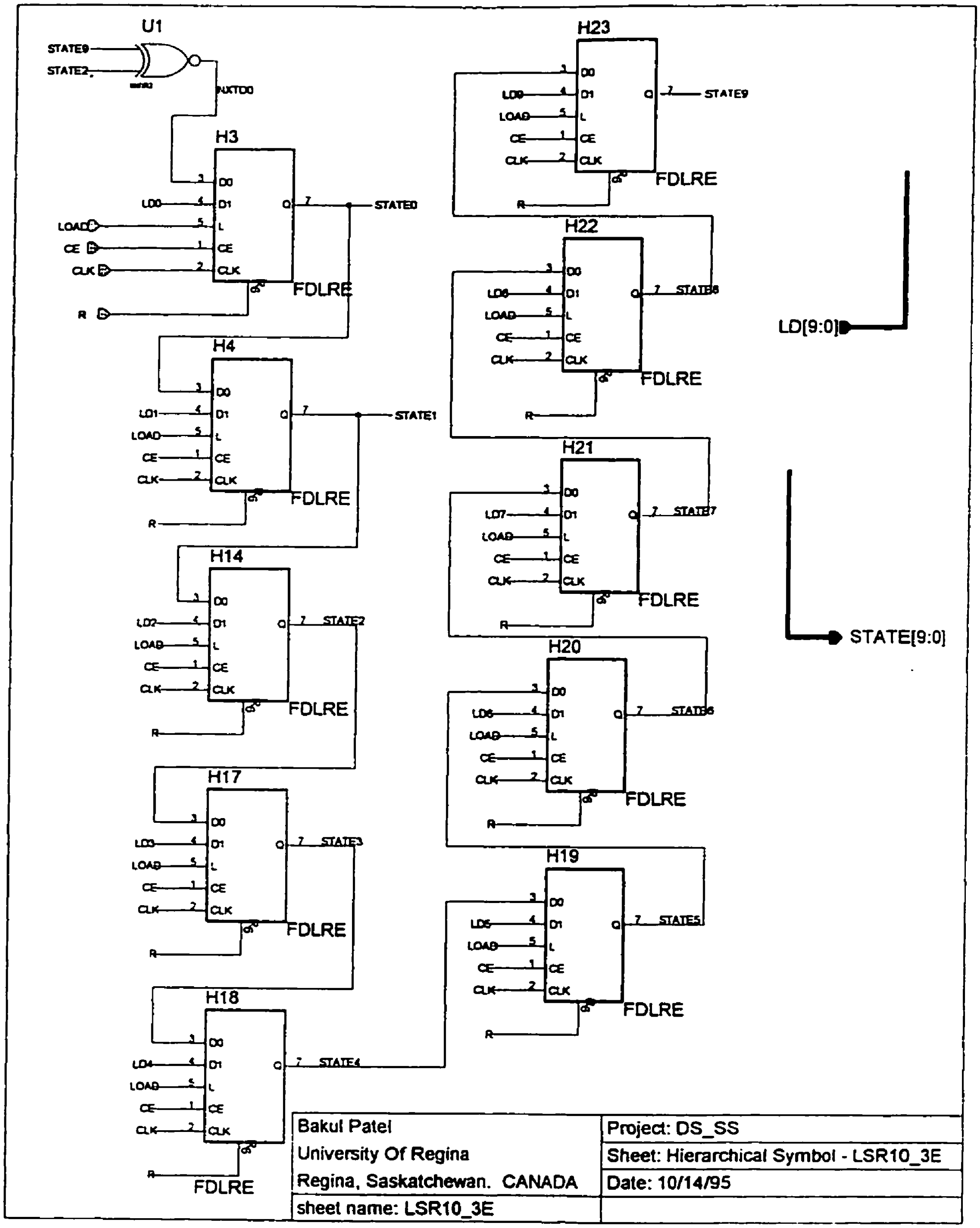



Figure 4.6 Schematic for 1023 code generator

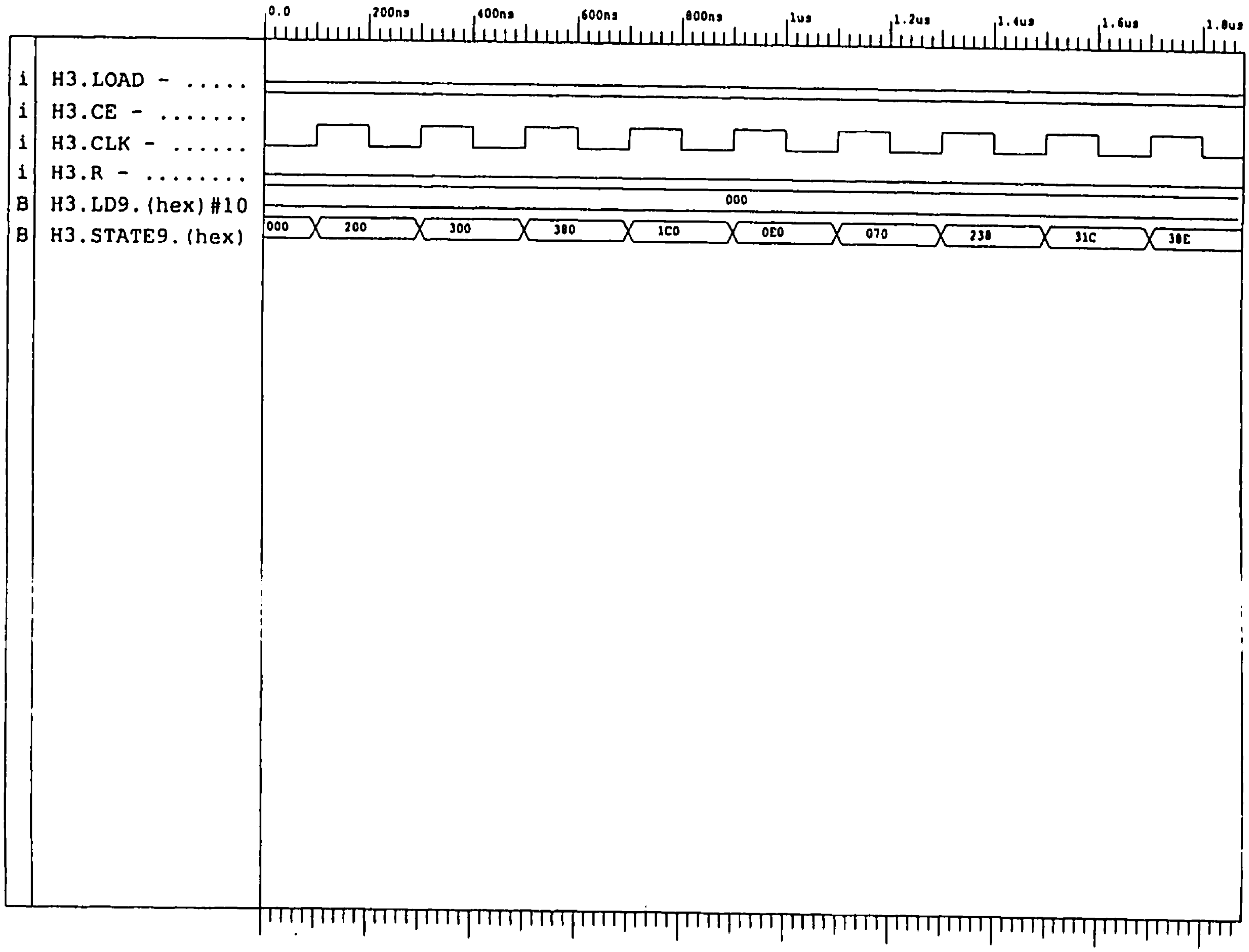



Figure 4.7 Initial simulation of the code generator.

## *4.4 Code sliding and offsetting*

An important component of the spread spectrum system is the code slider which is able to slide and offset the phase of the local reference code to synchronize with the phase of the incoming signal. In chapter three the proposed system introduced the method of synchronizing using the coarse and the fine sliding of the phase. The method describes how the phase of the local PN code is shifted in half chip steps, with the output of the synchronization detection circuit being the lock indicator. If the local code is shifted to be out of phase by half a chip out of phase from the received spread signal then the output of the synchronization detector will fall sharply. This is a property of good autocorrelation. After the detection of this initial synchronization the phase of the local code is shifted in steps of 1/256th of the chip to determine the peak of correlation.

### 4.4.1 Coarse sliding

As the PN code is shifted in phase with respect to the incoming signal the output of the correlation detector will start to rise from 1 chip away and reach a maximum at full synchronization. In order to search this synchronization point a coarse slide of the PN code can be made so that the local PN code jumps or slows down by half a chip. This can be achieved by shifting the phase of the clock used to generate the PN code. This phase shifting is done by deleting a half clock period for advancing the code by half a chip or by inserting an extra half clock period for retarding the code by half a chip. The proposed method uses sequential logic to insert and delete half of the clock period which is fed to the PN code generator. The logic is structured so that the insert and delete control lines are driven from the system's microprocessor. Figure 4.8 shows the insertion and deletion of the clock pulse for phase sliding forward and backward.

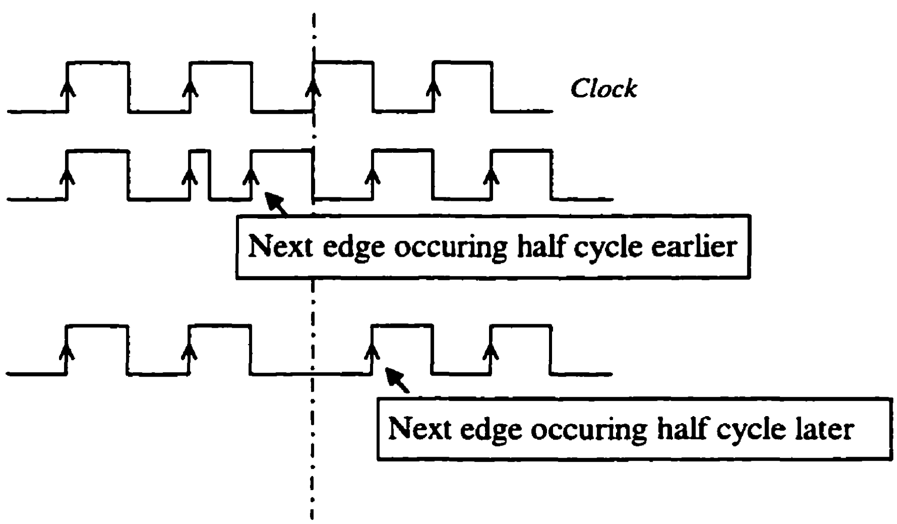



Figure 4.8 requirement for coarse sliding.

The second wave form in the above figure shows that for advancing the clock phase, the next active edge of the clock must occur half a clock cycle earlier than the scheduled time. Similarly the third waveform shows that for retarding the clock the next active clock edge should be missed and asserted half a cycle later than the scheduled time. The vertical dotted line in the above figure indicates the scheduled time of a normal active edge.

The approach for the design is achieved from visual inspection of the Figure 4.8. It can noted that that the phase of the clock after advancing and retarding the clock by half a cycle is the same; i.e. 180 degree out of phase before the process. The design for phase advance is achieved by monitoring the active clock edge ( denoted by arrow). Upon detection of the edge the output is switched to the phase inverted clock after some delay.

This delay is not critical because all the flip-flops used in the design are edge triggered and therefore can be as small as the propagation delay of one logic gate. This process is shown in Figure 4.9 below.

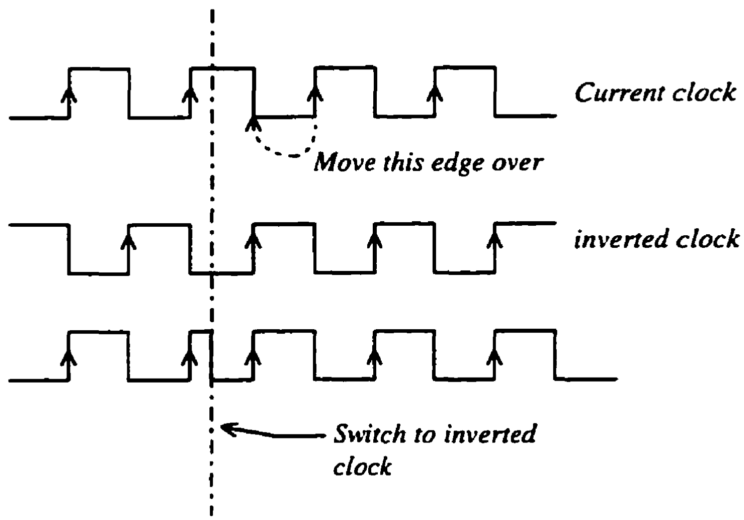



Figure 4.9 Chip insertion / phase advance

The design for clock phase retarding uses a similar approach as the clock advancing. Since the resulting phase of the clock is an inverted phase of the current clock, the circuit used for the advancing can be used for retarding. The difference being upon receiving the command for clock retard the first two active edges are monitored. After the first edge the final output is disabled when the logic level of the current clock is reached to low (logic zero). From this point the process is similar to that of clock advance except that the output is disabled. The next active edge is then detected and after a fixed delay the clock is switched to the inverted phase of the current clock. The logic level of the inverted clock is now monitored which upon reaching a logic low enables the clock output. The output of the circuit is shown in the Figure 4.10.

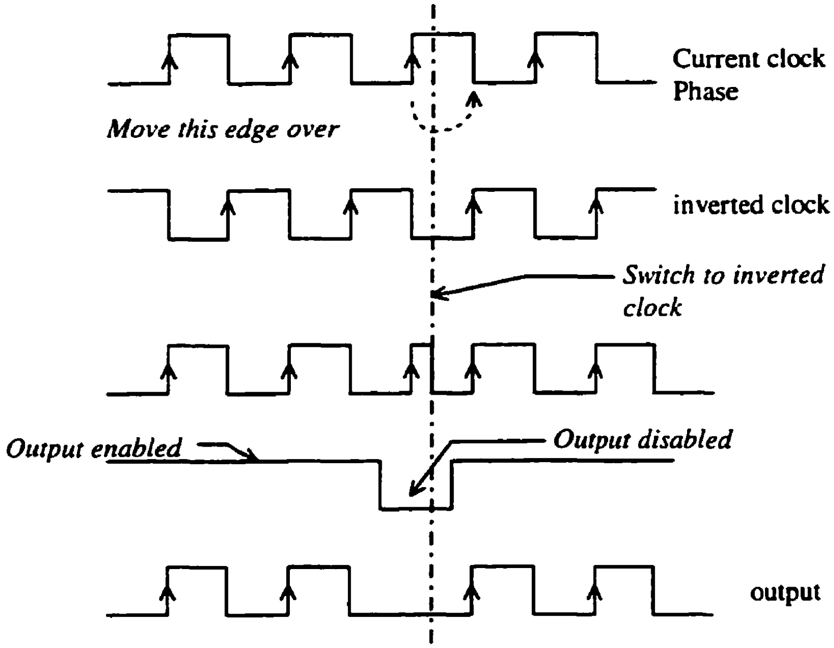



Figure 4.10 Chip deletion / phase retard.

The insert and delete commands are asynchronous to the chip clock, this leads to the extra sequential logic for synchronizing the commands. The commands are latched and on the arrival of the active edge of the chip clock the latches are cleared. The clearing of the commands cannot be done at the instant of the active edge of the clock, but after the switching of the clock to the inverted clock has taken place. To ensure this, the reset signal is derived from an exclusive OR gate whose inputs are on two sides of an inverter. The inverter in a FPGA is forced to be the delay from input to output delay of a Configurable Logic Block(CLB). Figure 4.11 shows the schematic for the chip inserter and deleter circuit, the delay for the reset signal is achieved by the module "clbmap" (U22). Figure 4.10 shows the method for retarding the phase of the clock. The back annotated simulation of the design is shown in Figure 4.4 and 4.5 for "clock advance" and "clock retard" respectively.

The coarse sliding of the PN code is utilized to do the initial search for the synchronization. Upon being half a chip away from being fully synchronized the output of the correlator is higher than elsewhere. This determines the peak of the auto-correlation curve. In order to synchronize the local PN code to the received signal to within 1/256th of a chip, more precise sliding is necessary.

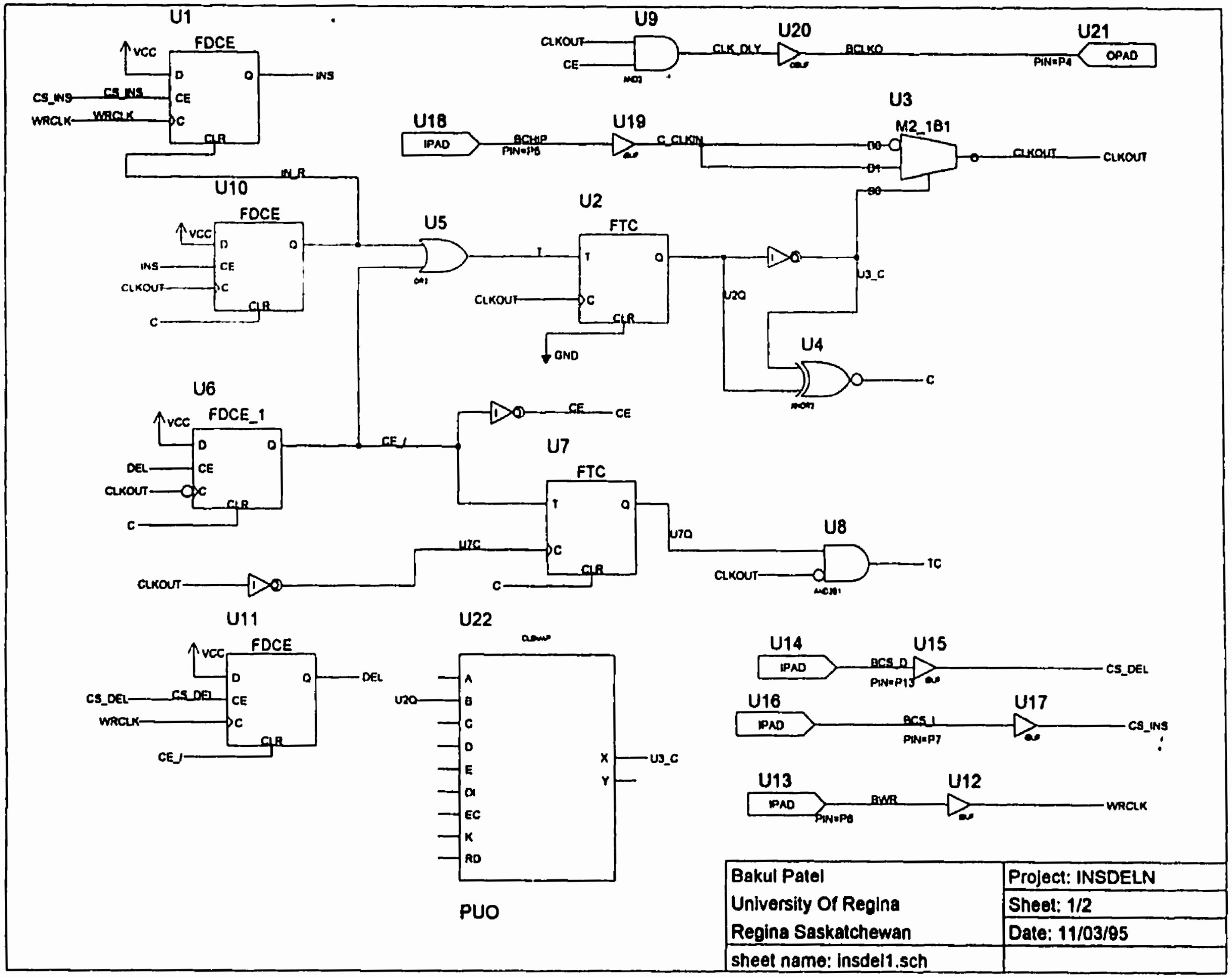



Figure 4.11 Schematic for advance /retard of the chip clock

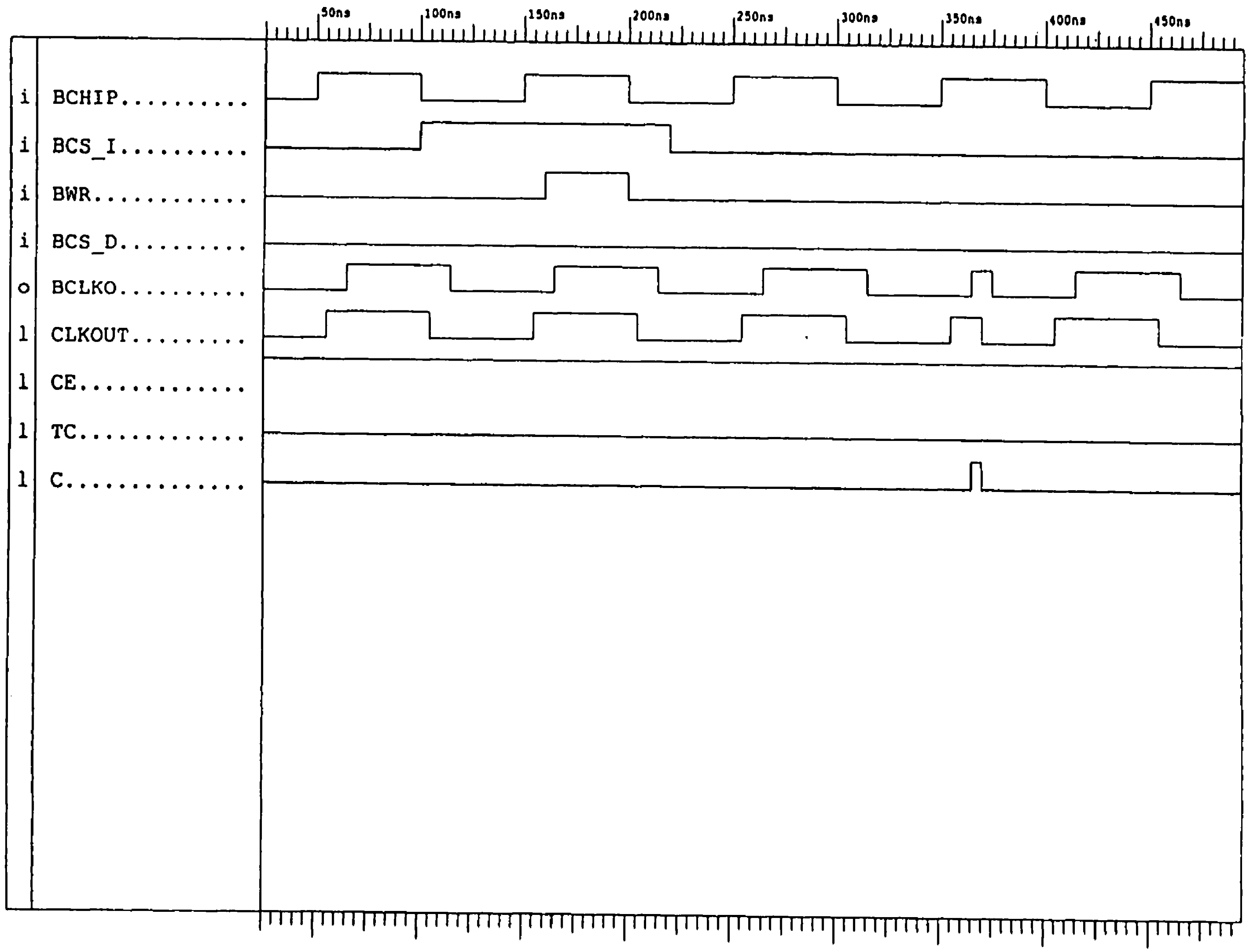



Figure 4.12 Simulation of clock advance.

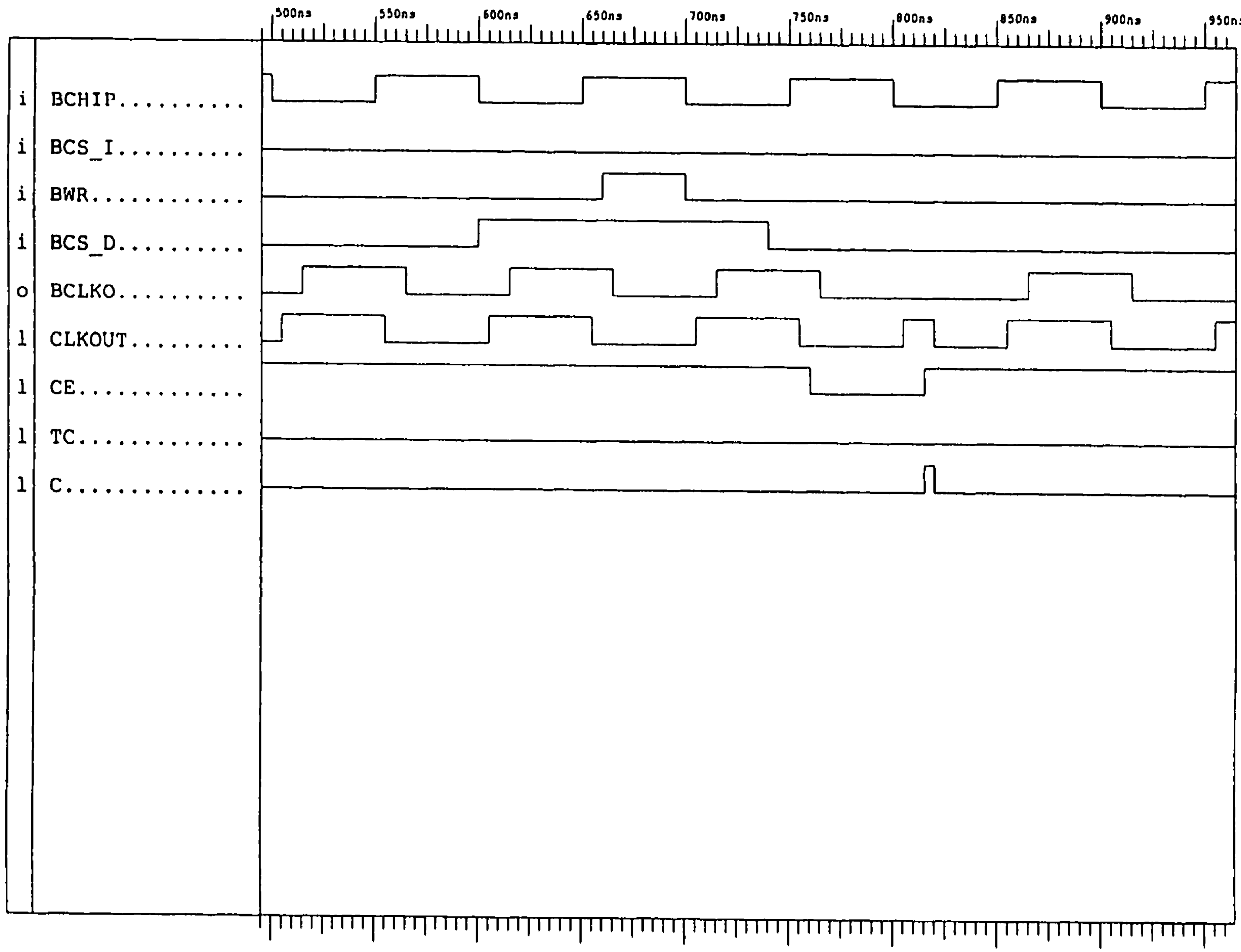



Figure 4.13 Simulation for Clock retard.

### 4.4.2 Fine PN code sliding.

After coarsely aligning the PN code, the peak of the auto-correlation function must be determined more precisely. The synchronization must be within one half of the carrier cycle. This would be to within 1/256 of a chip of the PN code. The fine sliding of the local PN code is achieved using a Phase Locked Loop(PLL).

The PLL is generally used to keep a particular system on track with a known reference. A typical PLL consists of a voltage controlled oscillator, a phase detector and a loop filter. The PLL is normally setup as shown in Figure 4.14 [28].

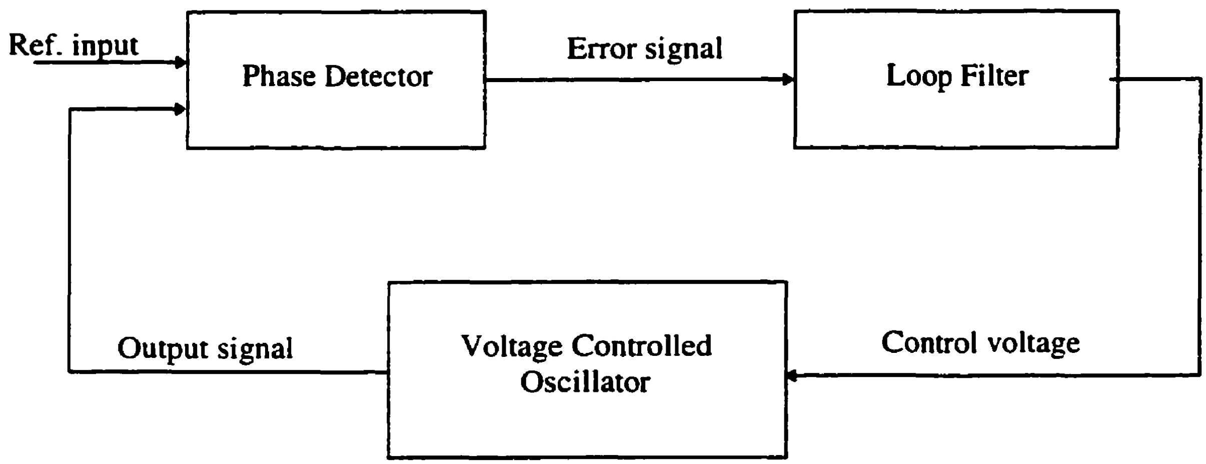



Figure 4.14 Phase Locked Loop block diagram.

The VCO output is fed back to the phase detector which generates an error voltage in proportion to the error in phase of the output signal compared to that of the reference input. This error is then converted to a control voltage, to which the VCO responds to minimize the error. When the phase error is reduced to minimum, the PLL is said to be in lock. If the phase of the reference input changes the PLL tracks this phase change and the output attains the same phase as that of the reference.

The reference used in most PLL systems is considerably lower in frequency than that of the output signal. This requires the output signal to be scaled down such that the two inputs entering the phase detector are of the same frequency. This scaling down of the output signal is normally achieved by using a counter to divide the output signal to match the reference. An alternate method employed for scaling down the output signal is by using heterodyne mixing of the output signal to a lower frequency. This mixing can be implemented by using one or more intermediate stages. However the local oscillators used in the mixing should be derived from the same source as that of the reference signal. The phase of the mixed down signal is a direct representation of the phase of the output of the VCO. The advantage of this method is that the VCO output frequency does not have to be an integer multiple of the reference frequency. Figure 3.17 in chapter three shows the DPLL for the transmit chip clock generator.

The PN code clock is generated using a PLL for both the transmit and receive sections. The reference to the PLL is derived from the systems reference; 11 MHz crystal oscillator. The derived reference can be altered such that its phase can be set digitally with respect to the original signal. This altered reference which is different in phase but equal in frequency is then used in the PLL. The reference used in this system is 43 kHz, which is derived from the 11 MHz by using a 8 bit counter (11 MHz ÷ 256 = 43 kHz). This 8 bit counter establishes the resolution of the phase steps which can be altered on the secondary reference. The CW ranging system uses this technique to change the phase of the carrier by a known amount, the same principle can be applied to the PN code clock. [15]. The following figure shows how the phase of the reference can be changed digitally.

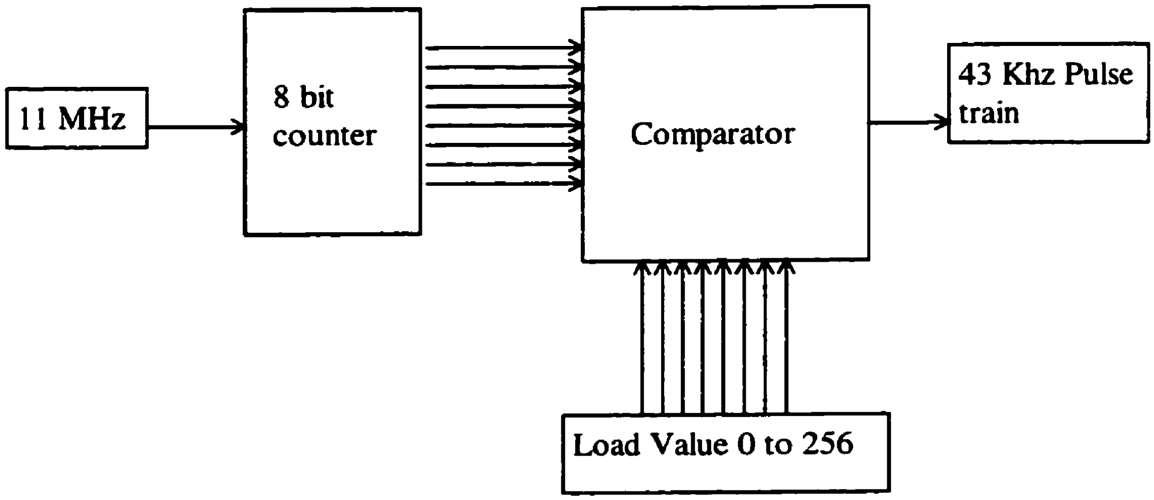



Figure 4.15 Digital phase offsetting circuit

The 8 bit counter is clocked from the 11 MHz reference in which the rollover frequency is 43 kHz. The comparator compares the state of the counter with a fixed load value; the output of the comparator is true only when the state of the counter is equal to the load value. This produces a pulse train with a frequency is 43 kHz but the phase is offset by the load value with respect to the 43 kHz signal available at the MSB of the counter. This configuration enables the PN code clock to be changed in steps of 1/256th degree steps of one cycle. Design of the PLL is implemented using the software and the algorithm given in "Phase-Locked Loops, Theory, design and applications" by Roland E. Best. A phase-step response of 450 micro seconds was achieved. This is the amount of time required by the PLL to settle on application of a step phase change.

In order to align the PN code, it is necessary to have a mechanism that can increment or decrement the code by 1/256 of a chip, defined here as a phase-step. The synchronization process requires one complete PN code cycle length to determine the degree of synchronization. The PLL reference is then adjusted to increment or decrement the code by 1/256 of a chip. The measurement of degree of synchronization cannot be started until the PLL has settled ( 450 μsec). This time determines the speed of synchronization of the hybrid system.

The above method has the advantage of stepping the phase of the PN chip clock by steps of 1/256th of a cycle, which is slightly more than one degree in phase. This leads the synchronization to within half a cycle of the carrier. The phase of the carrier can be determined by using the CW ranging method [21]. The disadvantage of this method is the lock time required for the PLL to reach a steady state and is in the order of one half of the PN Code cycle. This results in a time period where the next integration cycle cannot be started for at least 450 micro seconds. Considering the worst case, the time required for synchronizing can be derived as follows;

For Coarse synchronization :

- The case where no staggering is used, this gives a modulation cycle of 10 code lengths.
- If the whole code length is to be searched there are 2046 half chip steps in a code length. After each half chip step the correlator has to evaluate for a whole code cycle to verify synchronization. This would cause a maximum delay of 2.84 seconds ( 2046 steps * 1.39 msec { one code length time})
- This gives a total coarse acquisition time of 2.84 seconds.

For Fine synchronization :

- Number of phase steps required to scan one full chip is 256.
- Time required to evaluate the synchronization is again one full cycle after each phase change which is 1.39 msec.
- Total fine synchronization time to scan worst case would be 0.35 sec ( 1.39 msec(one code length time * 256 phase steps )

Therefore total worst case acquisition and synchronization time for one beacon would be 3.19 (2.84 + 0.35) seconds. If all the beacons were to be acquired and synchronized the worst case time for the system would be 28.71 seconds. The following table shows the calculation for worst case acquisition.

Table 4.1 Worst case calculation of acquisition and lock times.

| | | | |
|---|---|---|---|
| *Coarse synchronization:* | Number of half chip steps | 2046 steps | |
| | Time required for one increment (on modulation cycle, assuming no stagger; 10 code lengths) | 1.39 msec | |
| | Coarse synchronization time required | | 2.84 sec |
| *Fine synchronization:* | Number of phase steps in one chip | 256 steps | |
| | Time required for on increment (on modulation cycle, assuming no stagger; 10 code lengths) | 1.39 msec | |
| | Fine synchronization time required | | 0.35 sec |
| Total worst case acquisition and locking time required for one Beacon | | | 3.19 sec |
| Worst case acquisition and lock time for 8 beacons and master | | | 28.71 sec |

After initial synchronization lock, the phase of the carrier can be tracked to predict the phase of the PN code. The proposed method is not a very efficient one in terms of initial locking due to the sequential approach, but the local ranging applications does not require very fast lock times.

### 4.4.3 PN code Offsetting.

The maximal sequences have an important property of being able to shift the PN code to any desired phase. Many techniques have been suggested by Weathers, G. In 1972 and many others; the proof and observation is also shown in Appendix A of ARRL Spread Spectrum Source book. [29]

The method proposed for the hybrid system is relatively simple and the computational time to determine the offset is small. Figure 4.16 shows the block diagram of the Phase offset circuit.

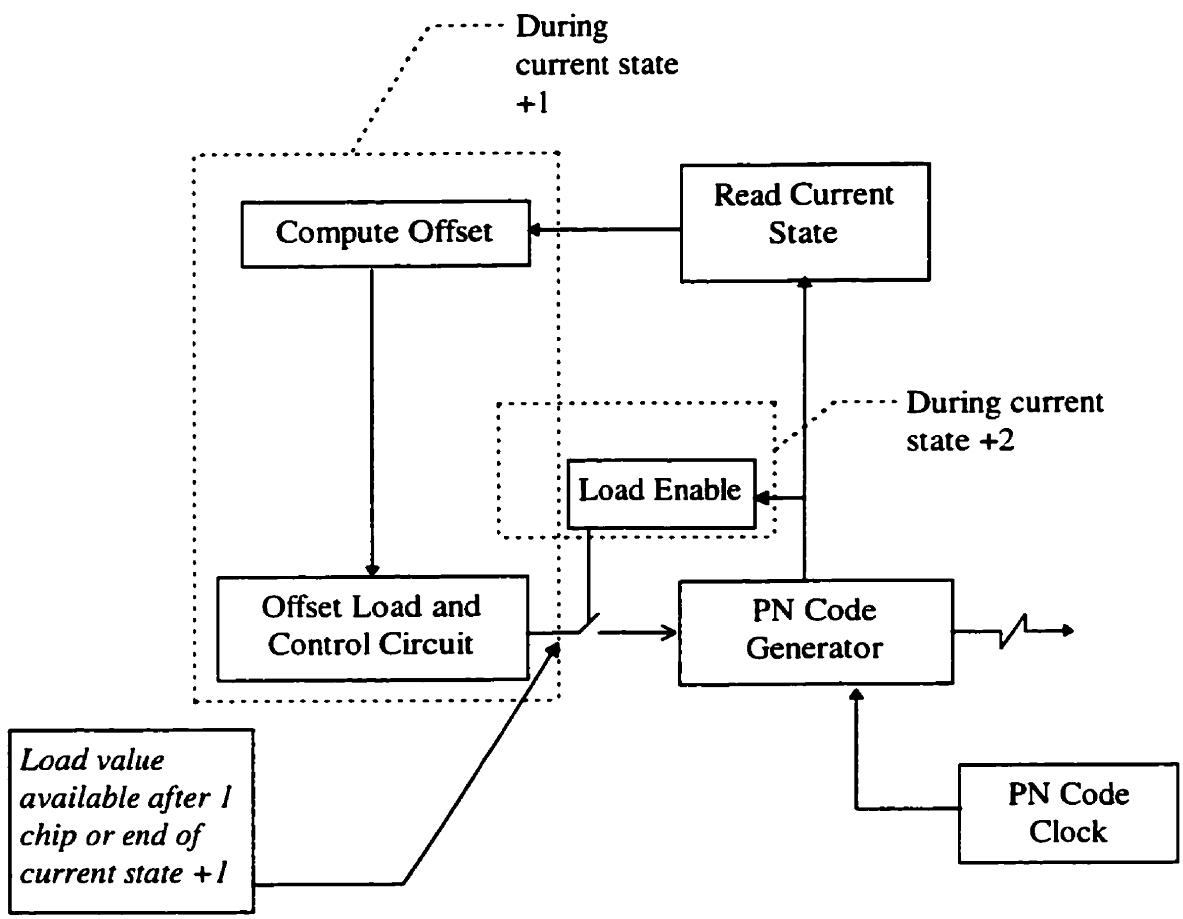



Figure 4.16 Phase Offset Block Diagram.

The PN code generator is capable of loading a state synchronously. The "Load enable" circuit is a comparator with one input being the state of the PN generator and the other a loadable value from the microcontroller.

The algorithm to phase offset the code generator is as follows,

- Receive the desired phase offset value from the calling subroutine.
- Read the "current" logical state ( state of all flip-flops) of the PN code generator.
- Determine the "current+1" and "current +2", logical states of the code generator.
- Determine the offset logical state of the code generator from a look up table with respect to the "current+2" state. The desired state is the phase offset from the load state.
- Insert the offset state in the "offset load and control circuit"
- Load the state comparator with "current+1" state. The output of the comparator compares the state of the code generator to the "current+1" state and produces a signal to load the PN code generator on the next active edge of the PN code clock. This new phase will have the same offset desired as that when the current state was read.

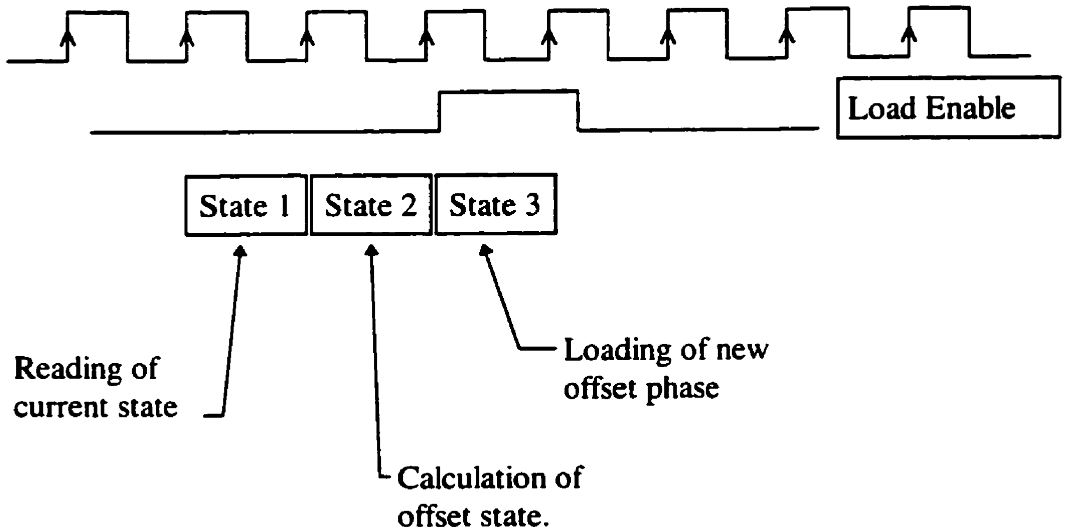



Figure 4.17 operation of phase offsetting.

## *4.5 Fast Tx switching for TDM.*

In most transceiver type systems where the transmit and receive frequencies are the same, the problem of the transmit carrier generator interfering with the receiver is of concern. The most common solution to this problem is to turn the transmit oscillator off or shift the oscillator frequency beyond the bandwidth of the receive front section. Currently the CW system uses the former technique of turning the oscillator off. The drawback of this method is that the turn on time of the transmit section is dependent on the lock time of the phase locked loop. This causes additional delay in transmit sections for time division multiplexing.

The proposed method is an attempt to enable a fast switch from receive to transmit mode of the system using time division multiplexing. Figure 4.18 shows the block diagram for the proposed carrier generation system.

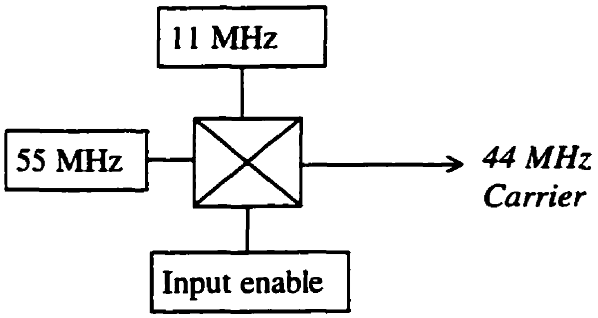



Figure 4.18 Carrier generation for TDM system.

The square box in Figure 4.18 can be either a digital mixer or an analog double balanced mixer. The digital mixer [25] in the simplest form, is a D flip-flop with clock enable. The higher frequency is fed to the D input of the flip-flop and the lower frequency is connected to the clock input; the output is the difference of the two frequencies {this theory is not applicable for all combinations; for details refer Appendix A}. The clock enable enables and disables the output to occur.

The same technique can be implemented with an analog mixer replacing the digital mixer with a DBM and the two inputs of the mixer connected through Gallium Arsenide fast switches. These switches control the output.

Chapter 5

# 5. Conclusions and Future Work

In chapter four the implementation and design issues were discussed along with some simulation results. Most of the proposed design for the hybrid Spread Spectrum system were verified with the simulation results. This chapter attempts to make conclusions based upon these results to determine the feasibility of the design. An effort is made to point out the advantages and disadvantages of the proposal keeping the implementation issues as the focal point.

The following components with their sub-components are discussed.

- Correlator.
    - The Double Balanced Mixer.
    - The Integrator.
- The PN code generator.
- The code Sliding circuit.
    - Coarse sliding.
    - Fine sliding.
    - Phase offsetting.
- The fast TX switch.

## 5.1 Correlator

The double balanced mixer selection criteria was based upon the assumption of the mobile being able to work within close proximity to the transmitters. The code being used is simple and has an unbounded cross-correlation value. After consulting with the application engineer at Minicircuits Inc., it was decided that their attenuator , which is also a mixer, was the best choice for doing the bi-phase modulation and demodulation.

Two methods are proposed for performing the integration after the carrier is despread. The first method, requiring the minimum of additional hardware, is not considered further because of insufficient information regarding the RSSI indicator . Its investigation is put forward as future work on the project. The second method involves an independent detection system which is most commonly used in DSSS systems. The reference to this method is the basic method described in many articles and textbooks[22,8]. It can be concluded that the integrator used should be such that the integration interval is an exact multiple of the code cycle. Although further work is required in this area, an integrator using digital sampling and digital signal processing technique could be utilized.

Locking and correlating are important parts of the DSSS system. More investigation on the performance of the detection of lock is necessary as part of future work of this project.

## 5.2 Code Generator

The code generator is a relatively simple element of the design. It must however have the ability to load an arbitrary phase value synchronously. This is important, especially for the receiver, to switch from one time multiplexed transmitter to another. The selection of the code and the code generator are interdependent. The reason for selecting the maximal sequence for the spreading code was to accommodate the code generator, along with other logic, on the single FPGA which is currently used on the existing CW ranging system.

## 5.3 Code sliding

The local PN code has to be either retarded or advanced to match the received code in order to find the maximum correlation value . This process is realized by advancing or retarding the PN code by half a chip to achieve a coarse lock. Upon verification of a coarse lock the fine sliding is done to lock the signal within half the carrier cycle or 1 / 256th of a chip. Since the process of code sliding is realized by three blocks, the conclusions on feasibility and performance are discussed in the following subsections.

### 5.3.1 Coarse sliding

The clock input to the generator is altered to effectively reduce or enlarge a chip time. The simulation results showed that the insertion and deletion of the clock can be successfully repeated on the command of a micro-controller. This approach was the simplest and it achieves the requirement of aligning the PN code at the point of maximum correlation. The coarse sliding could have been in jumps of one chip rather than half a chip. However the half chip jumps gives an added resolution to the coarse sliding and reduces the number of fine slides by one half.

### 5.3.2 Fine sliding

This process uses the same technique used by the CW ranging system to offset the phase of the carrier to any desired value using a phase locked loop. The method is implemented using digital mixers and using two different voltage controlled oscillators (for the beacons ) to avoid interference from each other. The disadvantage to this method is that the lock time for the synchronizing the code is increased by the lock time of the PLL. This means that, after the phase of the code is changed the integration at the correlator should be started after the PLL is locked (settled).

### 5.3.3 Phase offsetting

The PN code generator has the capability of loading synchronously any state from its parallel input. This capability is required for the mobile to switch from one transmitter to another. The major problem in achieving this function is to determine the desired state from the current state of the code generator. The microprocessor in the system makes this task easy as compared to an iterative, hard logic solution. A typical hardware design that would shift the phase by 16 states would require approximately 300 gates, which in terms of an FPGA would require 50 configurable logic blocks(Xilinx 3000 family). The proposed method does not produce an instantaneous phase change but waits until the third clock edge; giving time for computation. Future work in this area may involve the investigation of a faster algorithm to offset the phase of the generator.

## 5.4 Fast Tx switching for TDM.

Often in time division multiplexing single channel system transmitting and receiving at the same frequency is a problem. The CW ranging system uses TDM to switch between different transponders. The transponders have to receive the carrier and then transmit at their allotted time. This process requires the transmit section on the board to cease to avoid any interference with the received signal. The proposed method is an alternative to shutting the power off to the transmit oscillator. The method lets an oscillator operate at a frequency above the bandwidth of the receiver's front end and generate the carrier by mixing two signals, only when required. Current GaAs switches have nano second operation. It is important that the generation of the carrier be cutoff when not transmitting. The PLL can be prelocked (in case of phase offsetting) and hence does not require a fast locking VCO and conversely allows for an immediate change from receive to transmit mode.

## 5.5 System Feasibility

The proposed hybrid ranging system introduces a different method of obtaining range information. The main advantage of the hybrid system over the CW system is the elimination of the ambiguity. The proposal suggests that hardware be added to the CW system to convert it to a hybrid system.

The CW system is modified by adding components to transmit and receive the PN coded carrier. A staggered modulation cycle for the hybrid system was considered in which the transmissions overlap. This scheme encounters self jamming when the mobile is operating in close proximity to a transmitter. A totally TDM approach would avoid this jamming but the position update rate would be lower. Fortunately in this application the position update rate is not a compelling constraint. Therefore TDM modulation technique for the proposed hybrid is most suitable.

The components required for modifying the CW system are the code generator, the carrier spreader and despreader, the correlator and the code slider. The code generator is easily accomplished in the existing FPGA which poses no hardware changes. The carrier spreading and despreading requires an addition of a double balanced mixer. The proposed correlator uses an A-to-D and an integrator which requires additional hardware. The code sliding circuits can be accomplished in the FPGA except for the individual VCOs.

It is concluded that the proposed hybrid system is practical. Hardware can be added to the existing CW system to upgrade it to a spread spectrum system with no loss in existing performance and with the advantages that spread spectrum has to offer.

## *5.6 Further Work*

The correlation detector proposed is the major component which needs to be investigated and built to decide the overall reliability of the proposed system. Further work in this area would be helpful in making the hybrid system feasible.

The proposal for the hybrid system does not cover the microprocessor software which is also a major component in the hybrid system. Further work in this area along with the hardware implementation will ensure a working system.

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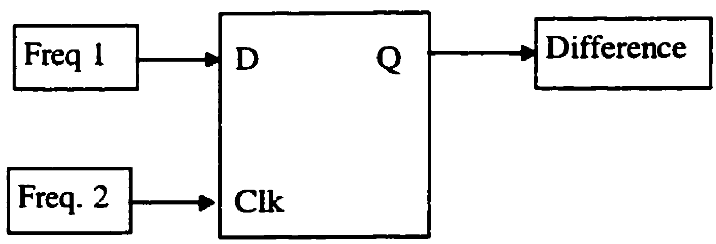
## Appendix A

# Digital Mixer.

The concept of the digital mixing has many advantages, as compared to the analog mixing. The sole purpose of mixing is to obtain the sum or the difference of the frequencies of the two mixing signals. The conventional method of mixing involves an analog double balanced mixer which produces the sum and the difference of frequencies of the two input signals. The desired signal is then filtered out using band-pass filters.

The digital mixer is implemented by a D flip flop, whose output produces the difference frequency of the two input signals. This property of the D flip flop, avoids the use of filter after the output, since only one frequency is produced.




***Freq. 1 > Freq. 2***
***Freq. 1 - Freq. 2 = Difference***

Frequency 2 slides in phase with respect to frequency 1, which causes the output to change the state by sampling the higher frequency. The rate at which the two wave forms slide pass each other determines the difference output's frequency and symmetry.

Let

Frequency 1 = $f_H$

Frequency 2 = $f_L$

then, $t_L = 1/f_L$ and $t_H = 1/f_H$

$t_L - t_H = t_{slip}$

Then,

$\frac{t_H}{t_{slip}} = N$, Where N is the number of $t_L$ cycles needed to produce one cycle of the output. The difference output has a 50 % duty cycle if N is even.

Therefore one cycle of the output has a duration of

$t_L * N = t_{out}$

For example consider the PN code sliding PLL, mix down stage where the two frequencies to be mixed down are 11852678 Hz and 11114600 Hz. The difference produces the clock for the PN code generator.

$f_H = 11852678$

$f_L = 11114600$

therefore,

$t_{slip} = 5.603$ nano sec.

N = 15.05884.

$t_{out} = t_L * N = 1.354870$ m sec.

$F_{out} = 738.078$ K Hz.

This digital mixer does not behave the same for all the frequencies, there are two major limitations as far as the mixing is concerned.

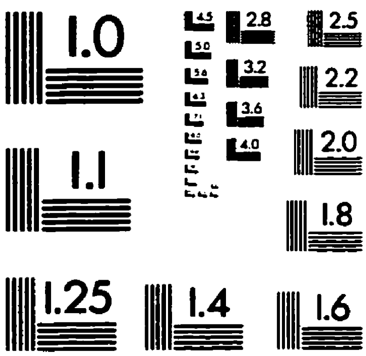
1) The output of the flip-flop changes state on every rising edge of the clock input which limits the highest frequency of the output to be half of that the lower frequency.

2) The above limitation also imposes on the higher frequency to be only 1.5 times that of the lower frequency.

Therefore the limitations are.....

$$f_H = 1.5 * f_L \quad \text{OR} \qquad N \geq 2 .$$

# IMAGE EVALUATION TEST TARGET (QA-3)

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