Spread Spectrum Communications and Jamming

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Lecture - 02
Direct Sequence Spread Spectrum System

Hello students, today we will discuss about the direct sequence spread spectrum communication technique. As discussed in the introductory module that direct sequence spread spectrum communication is one of the most popular spread spectrum communication technique. Other one is the frequency-hopping spread spectrum which we will discuss later on. Today, we will discuss the transceiver architecture, the signal model and the fundamental description of this direct sequence spread spectrum techniques in this module.

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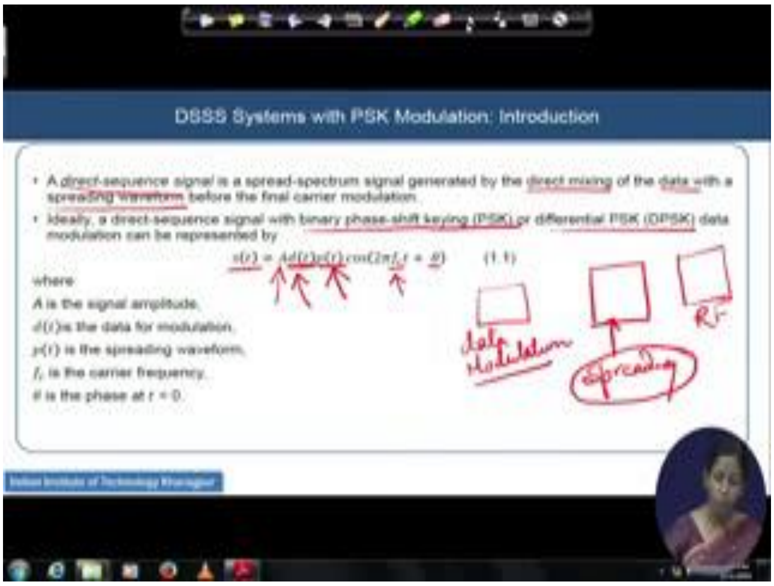

DSSS Systems with PSK Modulation: Introduction

- A direct-sequence signal is a spread-spectrum signal generated by the direct mixing of the data with a spreading waveform before the final carrier modulation.
- Ideally, a direct-sequence signal with binary phase-shift keying (PSK) or differential PSK (DPSK) data modulation can be represented by

$$s(t) = Ad(t)p(t)\cos(2\pi f_c t + \theta) \qquad (1.1)$$

where

A is the signal amplitude,

$d(t)$ is the data for modulation,

$p(t)$ is the spreading waveform,

f_c is the carrier frequency,

θ is the phase at $t = 0$.

Direct sequence spread spectrum as the name suggests, it is the signal model is obtained by the direct multiplication and direct mixing of this data with your spreading waveform. We understand that in the spread spectrum communications, the spread spectrum signal, it will have the extended waveform as compared to the data modulation bandwidth. And it will have an extended bandwidth also with respect to the underlined minimum required data modulation bandwidth. Here in the direct sequence spread spectrum system, the PN sequence or the spreading waveform will help us to extend the bandwidth of the spread spectrum signal as compared to the data modulated waveform.

Before the final carrier modulation, we utilize this direct mixing of the data with the spreading waveform. As I have already discussed that in the baseband processing of the receiver, we have three different stages of the modulation technique. The first stage is the data modulation, where actually the raw data is modulated over; is utilized to do the modulation of the carrier. And the famous techniques and the famous digital modulation techniques we utilize here is the BPSK, QPSK or the quadrature amplitude modulation or the QAM. And the modulation technique that I am referring in the spread spectrum communication is separate from the data modulation and this is called the modulation due to spreading.

And the final modulation apart from that is the carrier modulation or the RF carrier modulation that will be helping you to boost the signal from the baseband to the carrier to the RF carrier to the RF frequency where the transmission will actually take care of. When this spreading will be considered remember whenever we will talk about the modulation this is after data modulation, but before the actual modulation to the RF.

So, coming to the mathematical model of the direct sequence spread spectrum signal, if we consider that binary phase shift modulation keying is going on it is a and all or the differential phase shift keying is going on. Then using the value of that d t to be utilized from the BPSK modulation technique, we will be utilized in conjunction with the spreading sequence p t to generate the spread signal s t. The A term here in this case will be the signal amplitude, d t is the data for modulation as I have told already, p t is the spreading waveform, f c is the carrier frequency, and theta will be the phase at t equal to 0 time instant t equal to 0. And remember the form of this d t, the data modulation that we are considering here for this analysis will be the BPSK.

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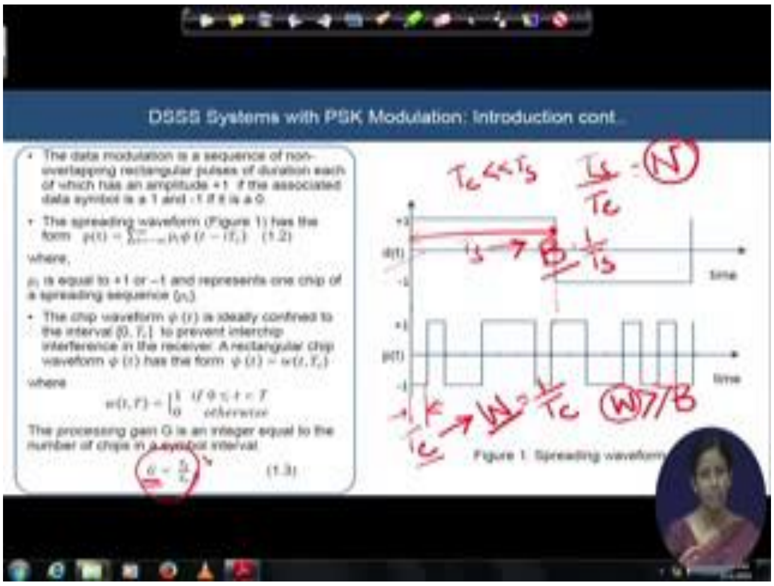

DSSS Systems with PSK Modulation: Introduction cont…

- The data modulation is a sequence of non-overlapping rectangular pulses of duration each of which has an amplitude +1 if the associated data symbol is a 1 and -1 if it is a 0
- The spreading waveform (Figure 1) has the form $p(t) = \sum_{i=-\infty}^{\infty} p_i \psi(t - iT_c)$ (1.2)

where,

p_i is equal to +1 or −1 and represents one chip of a spreading sequence $\{p_i\}$

- The chip waveform $\psi(t)$ is ideally confined to the interval $[0, T_c]$ to prevent interchip interference in the receiver. A rectangular chip waveform $\psi(t)$ has the form $\psi(t) = w(t, T_c)$

where

$$w(t,T) = \begin{cases} 1 & if\ 0 \le t < T \\ 0 & otherwise \end{cases}$$

The processing gain G is an integer equal to the number of chips in a symbol interval

$$G = \frac{T_s}{T_c} \quad (1.3)$$

Figure 1: Spreading waveform

So, if we go to the next slide, you will be able to see the form of this d t here. The direct sequence the BPSK modulation will be like this, where the incoming signal bit stream if it is given as 0 1 1 0 1 1 something like this. Actually wherever the BPSK modulation is there, the incoming bit stream the series of the 0s and 1 will be transmitted in the form of either plus 1 or minus 1 by the BPSK modulation; if it is a binary phase shift then we will have a shift of plus minus 180 degree corresponding to the incoming data bits. So, for 0, we will map the signal in the BPSK modulation as minus 1; and for plus 1, it will be transmitted as plus 1. So, for incoming sequence, actually we will be able to see the way the modulated data is available now with us for spreading.

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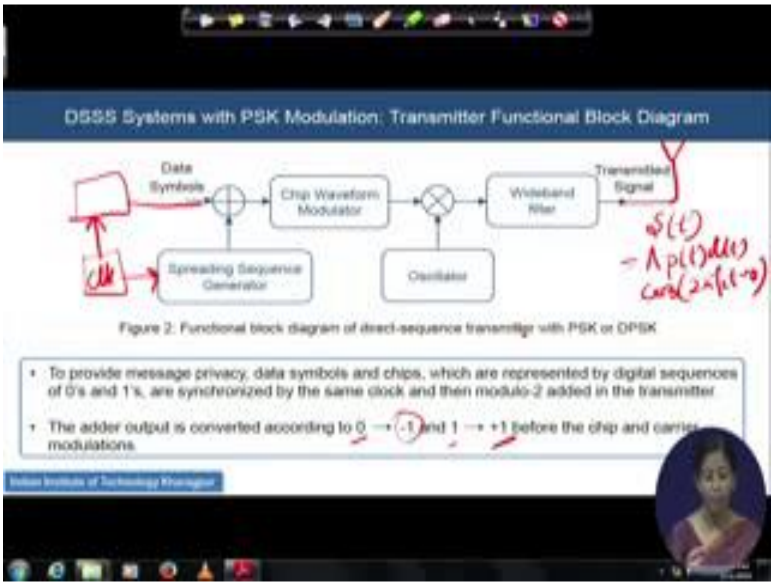

DSSS Systems with PSK Modulation: Transmitter Functional Block Diagram

Figure 2: Functional block diagram of direct-sequence transmitter with PSK or DPSK

- To provide message privacy, data symbols and chips, which are represented by digital sequences of 0's and 1's, are synchronized by the same clock and then modulo-2 added in the transmitter
- The adder output is converted according to 0 → -1 and 1 → +1 before the chip and carrier modulations

If we with this understanding of this data part with us, we would like to go back to the equation where we were dealing with this data part. See, if this data is given by the PSK modulation which is binary phase shift modulation then this s t hence with the we can write the s t as A p t cos 2 pi f c t plus theta plus this phase pi into d t. So, automatically the equation 1.1 can also be expressed in the form of this with the concept that there is a PSK modulation is involved in the process.

The spread waveform, how it will look like we will come little bit later, but let us first concentrate inside how the p t - the spreading waveform looks like. Remember before entering into the p t, I would like to mention here the symbol time of the data, we will mention here as p s. The p t which is the spreading waveform is usually given by the equation given minus infinity to plus infinity p i psi t minus i T c, where psi is taking care of the waveform and p i is either equal to plus 1 or minus 1. And it represents the chip of the spreading sequence p i. What is the form of the chip, so here we are not talking about a bit, here in the data case we will be talking about a bit and per bit duration we will have the multiple number of the chips, because there is a relative relation between the chip duration and the symbol duration in the spread spectrum communication.

Coming back to the concept of this waveform chip waveform, and the spreading waveform p t, we are seeing here that p t is also designed in such a fashion that the values the chip can take is either plus 1 or minus 1 over a duration of a chip. The chip duration, we will consider as T c. The waveform that p t psi t can take care of is usually the most common kind of waveform is a rectangular chip waveform given by the w t by T c and this rectangular waveform is defined as 1 if the time period is within 0 to the maximum period of capital T, and it will be 0 otherwise.

The figure here in figure one the spreading waveform is shown for the rectangular chip only. So, there are 2 questions coming in between because one is the relation between T s and T c what is the meaning coming out from see within the T whole duration of the symbol duration of the T s as T c is designed intentionally to be much, much lesser than my T s. As T c is designed much, much lesser than T s and this is my T s, and this was my T c. So, hence if I divide T s by T c, I will be ending up with certain integer number to get the integer number we usually try to keep one assumption that whenever the transition is happening for the data symbol and the chip symbol, they will be in sync both the direction on both the side of the data.

So, if this is maintained that they will be in sync transition will be in sync for both the p t and d t then definitely we will get the integer number of the chips involved inside the T s. This N the number n T s by T c is a very important parameter in the spread spectrum communication design; we call it usually the processing gain. And this is involved this is usually mentioned by the term G. It says actually within the symbol duration how many number of the chips you are designing for transmission.

Basically actually the one bit data is actually now spread over these many number of the chips capital N number of the chips. In terms of the bandwidth, if you wish to understand because it will be we are playing with the fundamentally we are playing with the bandwidth and the name suggests that we are expected to get an extended bandwidth. So, let us see how is it happening once I am actually multiplying the d t with p t as the signal model previously show here in equation 1 that the spread signal will be obtained by the multiplication of the d t with p t. So, once I am multiplying these two waveform d t with p t then at the end of this multiplication, I will be ending up with the chips only there would not be any existence of the bit. So, one we are ending up with the chip, so there will be instead of the bit rate the transmitted signal we will be we will be talking in the terms of the chip rate. And as the chip is involved, so after multiplication that means, after spreading you will be able to see this T c.

So, as T c is having is much, much less than T s if I consider that the corresponding bandwidth of this T c is given by W. And the bandwidth of the data modulation corresponding to T s is given by B, definitely B is equal to 1 by T s. And your W is equal to my one by T c then easily I can see that the after multiplication when I am ending up with T c I will be governed by the bandwidth W. Hence the spread signal spread spectrum signal bandwidth is becoming W which was earlier that the bit bandwidth was signal bandwidth was earlier B whereas. As T c is much less than T s so obviously, my w will be much, much greater than the B.

So, earlier when without spreading you were requiring a bandwidth of B to transmit the data signal d t, now you require a bandwidth of capital W to transmit the spread signal d t into p t that is why we tell the name as spread spectrum communications. We intentionally spread the data bandwidth of the data modulation than the minimum required bandwidth. And we have there is a processing gain involved in the whole process. Why do we do wish to do all that as indicated in the module, module one that this kind of communication ensures the message privacy or the message secrecy. And we wish to get the resilient against the interference or jamming signal.

This kind of the spreading of the waveform we will see a little bit later in a pictorial form the way the bandwidth is expanding after the spread spectrum communication, and how then in the receiver we are processing the signal such that we are getting the good resilience against any kind of narrowband interference or the narrowband jamming. Another point, in order to have the message privacy or message secrecy, the assumption of the perfect alignment of the transition of the p t and the d t is really very valid terms. So, we will consider throughout the explanation and description that there is a perfect transition match between our d t and p t.

This is the conceptual block diagram of generating the spread spectrum signal in the transmitter, where the direct sequence transmitter is utilizing the PSK either binary shift keying or the differential phase shift keying. The data symbols and the spreading sequences both in order to bring them in sync, we actually drive both the circuit by the same clock. Here we are having our data generated block which is generating the data symbols 0s and 1s. So, clock will be driving both the data generator and the spreading sequence generator at the same time.

And these are these are added in this block, and the before actually the chip modulation chip waveform modulation, they are added together and finally this is oscillator this is the modulate to addition going on inside it to give the effect of equivalent effect of the d multiplication of d t with p t. The output of this adder actually will be converted by this minus 1, 0 to minus 1 and 1 for bit number 1 to plus 1 if the coming bit is 0, it we will get minus 1. And then incoming bit is one we will actually get plus 1. Then the bits then the waveforms is having our chip modulation. And finally, here is the carrier modulation going on.

See in the practical circuit, we add the wideband filter here our amplifiers and add wideband filters before transmitting the signal from here. Here is the s t that we had already shown you earlier which governed by A p t d t cos 2 pi f c t plus theta, the signal we had generated earlier is getting transmitted. But before that we have to pass it through a power amplifier to boost up the power level, because the signal is expected to traverse a long distance over the wireless communication channel. And the wideband filter is utilized to cut out the unwanted signal portion of the spectrum out of the band of our interest.

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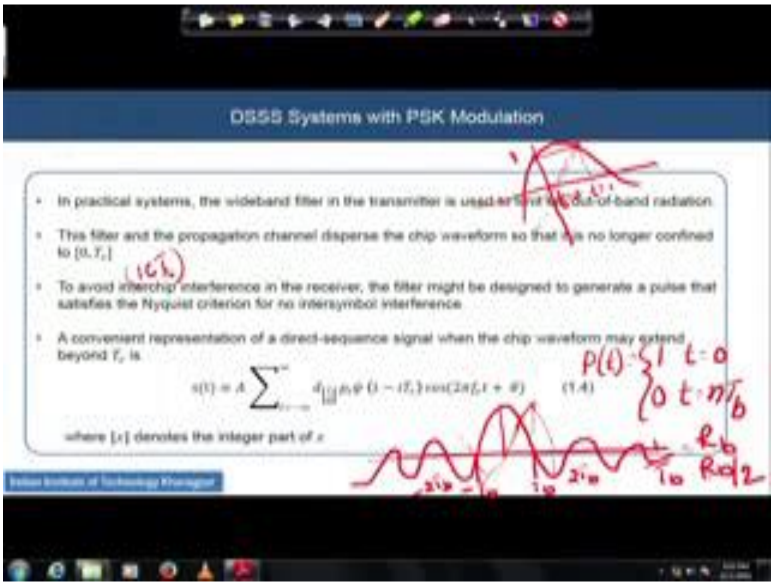

DSSS Systems with PSK Modulation

- In practical systems, the wideband filter in the transmitter is used to limit the out-of-band radiation
- This filter and the propagation channel disperse the chip waveform so that it is no longer confined to $[0, T_c]$
- To avoid interchip interference in the receiver, the filter might be designed to generate a pulse that satisfies the Nyquist criterion for no intersymbol interference
- A convenient representation of a direct-sequence signal when the chip waveform may extend beyond T_c is

$$s(t) = A\sum_{i=-\infty}^{\infty} d_{\lfloor i/G \rfloor} p_i \psi(t - iT_c)\cos(2\pi f_c t + \theta) \qquad (1.4)$$

where $\lfloor x \rfloor$ denotes the integer part of x

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$$P(t) = \begin{cases} 1 & t = 0 \\ 0 & t = nT_b \end{cases}$$

Usually what happens in the practical communication system is whenever you have started with a nice rectangular chip waveform, but once this chip waveform is passed through a wideband filter or through the wireless communication channel both the filter as well as the channel they disperse the signal and the waveform gets changed like this. So, the fundamental effect that we see is that there is a spillover because of the dispersion of the filter as well as the wireless communication channel, there will be a spillover of the power of say t equal to 0th pulse over the t is equal to 1th pulse. The effect that we are considering here is we call it is an interchip interference, so there is interference from the previous chip to the next chip as if. And we need to take care of the nice filter design inside the transmitter, so that actually this effect can be nullified.

So, thing is we considered earlier that the chip is designed such a way the rectangular chips are designed in such a way that it will be confined within the duration of the 0 to T c and there will be a nice transition, which is in sync with the data. Now, that concept or that theoretical concept will be disturbed by the presence of this wideband filter as well as the wireless communication channel. So, the pulse design that I was mentioning that we have to take care of and we have to design the pulse in such a way that it satisfies the Nyquist criteria that confirms that there would not be any inter-symbol interference or interchip interference in this situation in between the transmitted symbols. So, hence when it is received, there would not be any effect of the interchip interference or the inter-symbol interference.

We will discuss here a little bit about what exactly is this inter-symbol interference effect, how can we design the Nyquist pulse. The Nyquist criteria is like this. Nyquist thought that the first criteria that Nyquist designed a pulse in such a way that the pulse will have equal to the value will be equal to 1 when t is equal to 0, and it will have the value 0 for any other t equal to say n into T b, where T b is the duration of the pulse. If I map it into our case, then we need a pulse where the value will be equal to 1 at t equal to 0; and its value will be exactly equal to 0 when t is equal to n into T c.

How the pulse will look like then the pulse will look like this we call it a sync pulse. The other pulse is the replica of the pulses are going like this. So, you are getting a peak value when others are other its corresponding pulses are not having any peak. So, the pulse we are Nyquist took and these are the one places where actually it is minus T b and this is plus T b. So, this is twice the T b value. This is minus twice T b value, and T b is equal to one by T b we will call the bit rate R b. So, if you design a pulse like this, it can be shown that you can transmit the data R b amount of the data using a bandwidth theoretical minimum bandwidth required is equal to R b by 2 in that since such situation.

But question is that it is really very hard to maintain the bandwidth within R b by 2 usually we see that this first criteria Nyquist first pulse design criteria needs some excess bandwidth.

So, what we try to do is Nyquist came up with a second kind of the pulse design, where he showed that the bandwidth further if we wish to reduce we can simply do it by increasing the distance increasing the width of the pulse, so that the width of the pulse that we are now talking about will be given by this. So, now, we will be having the two different situation two different values of the t for which the pulse will have the high value is equal to 1. And this is t is equal to 0, and say t is equal to 1, for both the cases the pulse will have at least show the value equal to 1. And hence it will we call it the controlling with controlled interference we can have we can design the pulse - the transmitted pulse.

But here remember when are having the controlled interference why I am saying it is a controlled interference because for t is equal to 0 the interference may be 0, but for t is equal to 1, you have some interference from the next pulse. But that is a the pattern is will be well-known, it is the criteria of the pulse design of the Nyquist pulse design criteria involved where actually it will help you to control the ICI or the inter chip interference in our case to a great extent. So, before transmitting or releasing the spread spectrum waveform in the air after power amplifier and the wideband filtration operation, we have to also take care of this pulse shaping. With proper shaping of the pulse only to control the inter-symbol interference in the receiver, we will release it in the air.

Now, with this understanding that now hence if there is a spillover of the pulse. So, for the duration of the T c then hence the direct sequence signal should not look like the way we have written it earlier. Now, the sequence will look like this where actually this part is talking about the integer part of this x i by G is the integer part of this x, this symbol is indicating the integer part of the element which is inside it. And how actually this i can go from this minus infinity to plus infinity depending upon the dispersion rate has happened to the effect of this symbol with the inter-symbol interference the chip waveform will look like this. And the data part is not now actually typically in the receiver you would not get the data received, typically for that instant. And the transmitted signal is definitely is getting reformed by this spilled over signal.

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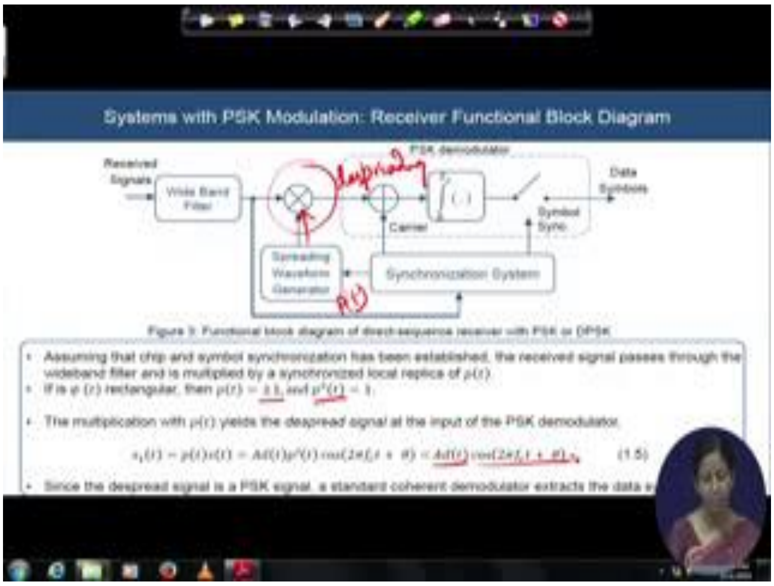

Systems with PSK Modulation: Receiver Functional Block Diagram

Figure 3: Functional block diagram of direct-sequence receiver with PSK or DPSK

- Assuming that chip and symbol synchronization has been established, the received signal passes through the wideband filter and is multiplied by a synchronized local replica of $p(t)$
- If is $\psi(t)$ rectangular, then $p(t) = \underline{\pm 1}$, and $\underline{p^2(t)} = 1$.
- The multiplication with $p(t)$ yields the despread signal at the input of the PSK demodulator

$$s_1(t) = p(t)s(t) = Ad(t)p^2(t)\cos(2\pi f_c t + \theta) = \underline{Ad(t)}\,\underline{\cos(2\pi f_c t + \theta)} \qquad (1.5)$$

- Since the despread signal is a PSK signal, a standard coherent demodulator extracts the data s

If we look at the receiver sector, the receiver functional block diagram conceptually will be looking like this. So, there you were sending the data after the wideband filter and here at the frontend, you need the wideband filter to capture the signal of your interest with the filter center frequency will be the center frequency of the transmitted 1 that is equal to f c and after extracting the synchronization information and the synchronized locally generated spreading waveform is utilized to de-spread the incoming signal. So, here we utilize again multiplier which multiplies the incoming received spread signal. And once this multiplication is done we are here receiving the de-spread signal, the operation this operation where we multiply the locally generated PN sequence which is exactly known apriori sequence that was used in the transmitter with the incoming spread signal we call this process the de-spreading.

The apart from the output of the de-spreading block the signal is entering into the PSK demodulator, which will demodulate the signal later on. But remember one thing as actually the p t, what we were generating is basically will be again a rectangular waveform, if we use the rectangular waveform in the transmitter, hence the value of the p t will be plus 1 minus 1. And once we are multiplying this we will be ending up with the p square t which will be always giving you the value of the 1. So, at the end of the de-spreading procedure process, you will be ending up with the signal A into d t multiplied with this carrier frequency cos 2 pi f c t plus theta.

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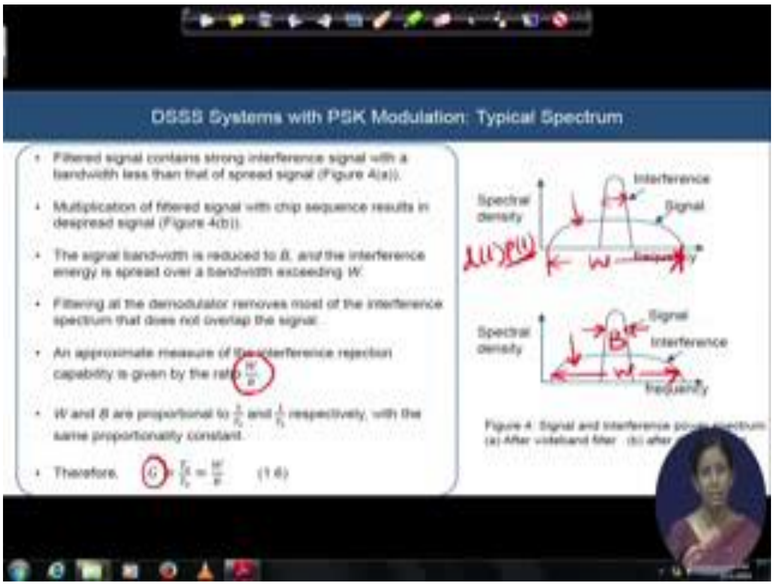

DSSS Systems with PSK Modulation: Typical Spectrum

- Filtered signal contains strong interference signal with a bandwidth less than that of spread signal (Figure 4(a)).
- Multiplication of filtered signal with chip sequence results in despread signal (Figure 4(b)).
- The signal bandwidth is reduced to B, and the interference energy is spread over a bandwidth exceeding W.
- Filtering at the demodulator removes most of the interference spectrum that does not overlap the signal.
- An approximate measure of the interference rejection capability is given by the ratio $\frac{W}{B}$
- W and B are proportional to $\frac{1}{T_c}$ and $\frac{1}{T_b}$ respectively, with the same proportionality constant.
- Therefore, $G = \frac{T_b}{T_c} = \frac{W}{B}$ (1.6)

Figure 4: Signal and interference power spectrum (a) After wideband filter (b) after

The de-spread operation what we have understood here in the mathematical form, it will be good now to see that how pictorial spectral wise, it will look like. Remember, so in the transmitter what we did we spread the signal, because we understood that d t into p t will spread the signal because it will be governed by the bandwidth of p t, because the T c is very less for p t. So, bandwidth was high and hence actually the signal bandwidth was spread over W now. It was the spread signal. And interference who actually does not know what exactly the sequence you have utilized the sequence is a key secret, secret key for you. So, interference will be of a narrow band interference having a bandwidth lower than the spread bandwidth. When you have received the signal you have received the signal combined with the interference who is having the spectrum orientation like this.

Now, inside, so this W by B is taking care of the fact how good we will be in a rejection of the interference. More actually the ratio will be more actually the gain will be and more you will be the resilient against the interference. In the receiver, after de-spread operation what will happen after de-spreading, the signal bandwidth will again contract will again they will be compressed where the bandwidth of where from we started with. But as now the interference is getting multiplied with the locally generated p t which was not done earlier, hence p t will help this interference to spread over the bandwidth W.

Remember one thing as we are considering the gain bandwidth product of the whole design is constant. So, when you are increasing the bandwidth the gain of the signal is expected to come down. So, when we expanded the transmitted signal in the transmitter over the bandwidth, see with the bandwidth the power was reduced it was spread over the whole bandwidth. Once you have compressed the signal in the receiver after de-spreading your bandwidth has squeezed and the signal power has come back. And it is not the back it will be even higher than the transmitted signal power because you will be having a power gain also by the term of this processing gain G.

Here actually in the case, the thing is opposite in case of your interference. Now, they have got spread over a bandwidth of W. So, whatever the power with which they transmitted now it has come down to a very low level. So, it will be equivalent to the noise, it cannot its power is very much low compared to the signal power which has already got boosted up; and it will be easy for us now to detect the signal in presence of this interference power. So, that is the beauty of this kind of spread spectral communication, you are getting resilience in presence of the interference and you can actually very nicely detect your own signal in presence of the interference.

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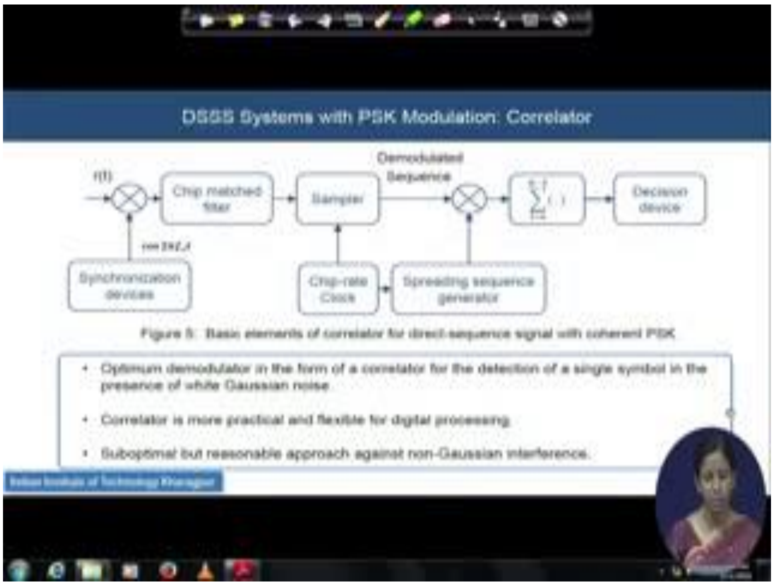

DSSS Systems with PSK Modulation: Correlator

Figure 5: Basic elements of correlator for direct-sequence signal with coherent PSK

- Optimum demodulator in the form of a correlator for the detection of a single symbol in the presence of white Gaussian noise.
- Correlator is more practical and flexible for digital processing.
- Suboptimal but reasonable approach against non-Gaussian interference.

And the easiest way of this modulation technique is to replace and to go ahead with the correlated architecture which is basically the match filtered plus the correlator architecture that we will discuss in detail in the later module. And this is the more easiest way the way we can implement in practice the match filtered based, and the correlated match filtered and the correlated based demodulated circuit for the spread spectrum communication system. This is a optimum demodulator in the form of this correlator circuit, where actually the detection of the signal in the presence of the white Gaussian noise can be possible. This correlated is very as I have told it is a more practical and the flexible for the digital signal processing and though the whole design is sub-optimal, but it is a reasonable approach against any kind of a non-Gaussian interference.

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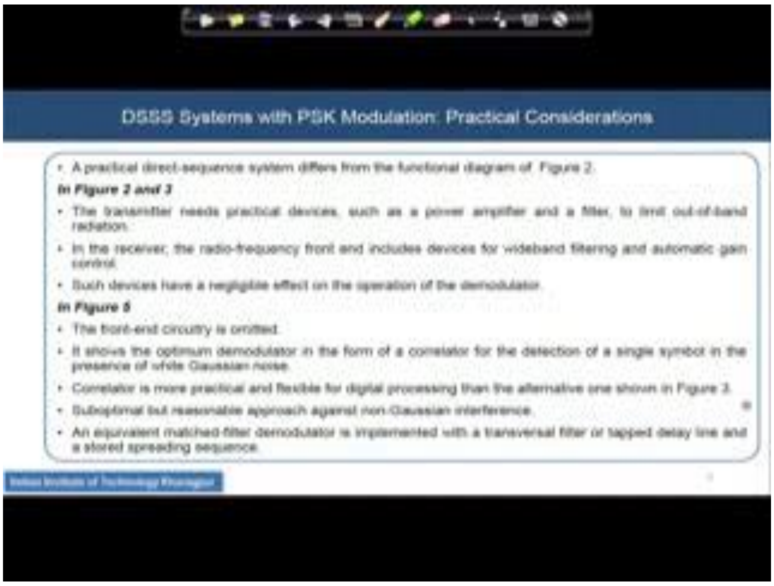

DSSS Systems with PSK Modulation: Practical Considerations

- A practical direct-sequence system differs from the functional diagram of Figure 2.

In Figure 2 and 3

- The transmitter needs practical devices, such as a power amplifier and a filter, to limit out-of-band radiation.
- In the receiver, the radio-frequency front end includes devices for wideband filtering and automatic gain control.
- Such devices have a negligible effect on the operation of the demodulator.

In Figure 5

- The front-end circuitry is omitted.
- It shows the optimum demodulator in the form of a correlator for the detection of a single symbol in the presence of white Gaussian noise.
- Correlator is more practical and flexible for digital processing than the alternative one shown in Figure 3.
- Suboptimal but reasonable approach against non-Gaussian interference.
- An equivalent matched-filter demodulator is implemented with a transversal filter or tapped delay line and a stored spreading sequence.

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We will go ahead with the next analysis of the direct sequence spread spectrum system based on this architecture receiver architecture. Remember whatever the initially two figures conceptual block diagram figures we have shown, we excluded the power amplifier in the transmitter, and we also excluded the automatic gain control sector in the receiver. Understanding the fact that such devices are not having any significant effect on the demodulation operation. So, we will be proceeding with those algorithms, but in practice we will have all those RF circuitry involved in front of that baseband module that we have shown in figure 2 and 3.

And in figure 5 also going by the same effect we have omitted the frontend independent blocks like your wideband filter followed by the low noise amplifier and the automatic gain control. We will give more thrust on the demodulator circuitry optimum demodulator circuitry, which is designed here in a form of a correlator for the detection of this signal symbol in the presence of white Gaussian noise. And the equivalent match filter demodulator will be is actually it is basically implemented in practice by means of a tabbed delay line or the transversal filter. And the stored spreading sequence is also utilized for the online or offline processing of the de-spreading in the receiver circuitry.

So, in the next module, we will continue with the architecture designed architecture already mentioned in the figure five in detail we do the performance analysis of the direct sequence spread spectrum systems.