Spread Spectrum Communications and Jamming

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Lecture - 05
Frequency-hopping Spread Spectrum System

Hello students, today we will start the spread spectrum communication jamming, second type of the jamming and spread spectrum communication techniques which is a Frequency-Hopping Spread Spectrum Systems.

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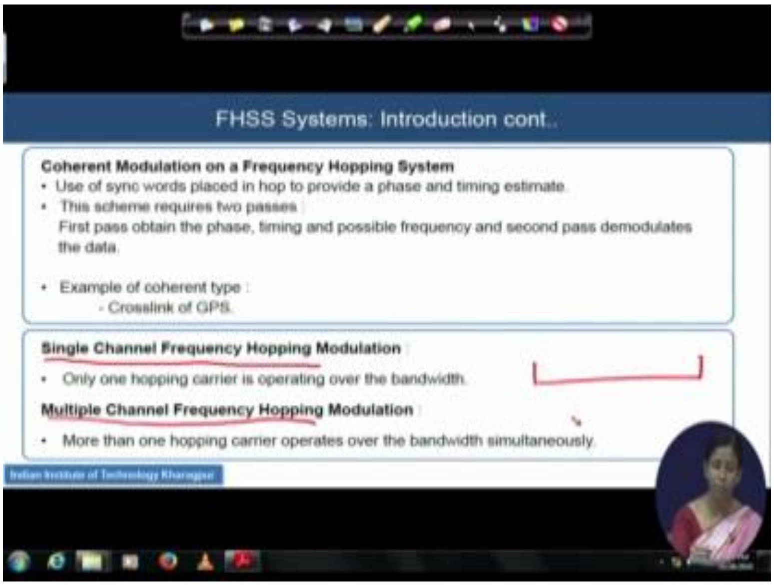

FHSS Systems: Introduction cont..

Coherent Modulation on a Frequency Hopping System
- Use of sync words placed in hop to provide a phase and timing estimate.
- This scheme requires two passes :
  First pass obtain the phase, timing and possible frequency and second pass demodulates the data.
- Example of coherent type :
  - Crosslink of GPS.

Single Channel Frequency Hopping Modulation :
- Only one hopping carrier is operating over the bandwidth.

Multiple Channel Frequency Hopping Modulation :
- More than one hopping carrier operates over the bandwidth simultaneously.

Frequency-Hopping Spread Spectrum Systems is a another type of spread spectrum technique where the center frequency of the transmission of the carrier frequency will be periodically changing according to some PN sequences how it is something like this. Suppose, we have wideband of channel available which is equivalent to the signal bandwidth available for the transmission. Given this wide bandwidth of say W we will divide this available bandwidth into several channels. Say I have capital N number of channels; now my carrier frequency of data transmission will be hopping from channel 1 to channel 2 to channel 3 to channel 4 to 5 dot dot dot dot channel number capital N. How I will be hopping will be depending upon the PN sequence code. This sequence will be inherent to a system designer and the type of the design that you are doing. So, the key of this whole system design is the design of the secret PN sequence code.

The data modulation that will be going in between will be of different types; it can be a coherent type of modulation or it can be non-coherent type of the modulation. The famous non-coherent type of the modulation that is usually used for this frequency-hopping spread spectrum systems are the MFSK - the multiple frequency shift keying, or the differential phase shift keying. For MFSK, we within a single hop time two or more frequency offsets are possible, whereas for our differential phase shift keying the fixed number of the symbols are placed per each hop. A good example of this DPSK is the milstar MDR or the milstar medium data rate systems.

Now, coming to the coherent modulation type of frequency-hopping system, this kind of the system utilizes sync word which is utilized for getting the synchronization information by means of synchronization. I mean the phase and the timing estimate that will be performed at the frontend of the receiver before any kind of the de-hopping and the data detection techniques. The scheme requires basically of two phases. In the first phase of coherent modulation frequency-hopping system, you will have the phase timing and the frequency information extracted by some estimation technique. And in the second phase, only you can demodulate the data a very good example of such system is the crosslink of GPS - the global positioning system. Frequency-hopping spread spectrum system further can be classified into two types; one is the single channel frequency-hopping, and the second one is the multiple channel frequency-hopping.

See for the single channel frequency-hopping only one hopping carrier will be there operating over whole bandwidth. And in multiple carrier frequency offset obviously, we will have the multiple carrier frequencies each of these carrier frequency is getting hopped simultaneously over the whole bandwidth available based on the PN sequence code you have generated for that typical system.

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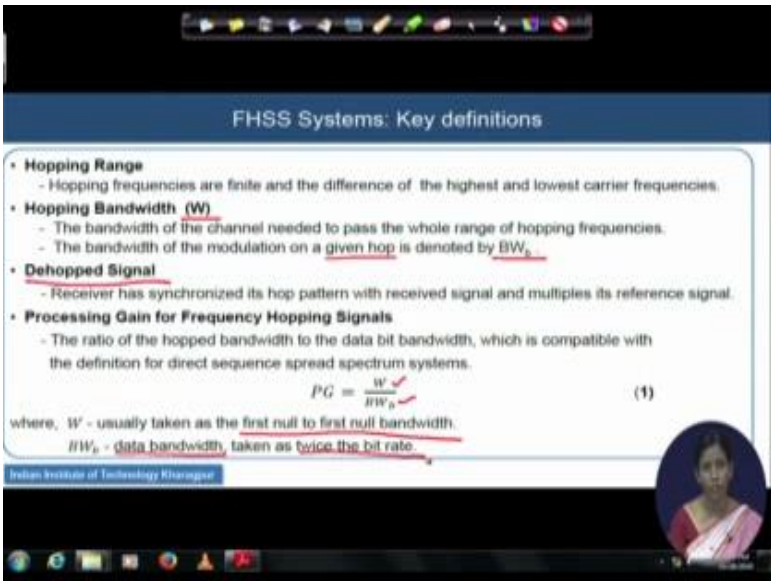

FHSS Systems: Key definitions

- **Hopping Range**
  - Hopping frequencies are finite and the difference of the highest and lowest carrier frequencies.
- **Hopping Bandwidth (W)**
  - The bandwidth of the channel needed to pass the whole range of hopping frequencies.
  - The bandwidth of the modulation on a given hop is denoted by BW_b
- **Dehopped Signal**
  - Receiver has synchronized its hop pattern with received signal and multiplies its reference signal.
- **Processing Gain for Frequency Hopping Signals**
  - The ratio of the hopped bandwidth to the data bit bandwidth, which is compatible with the definition for direct sequence spread spectrum systems.

$$PG = \frac{W}{BW_b} \qquad (1)$$

where, W - usually taken as the first null to first null bandwidth.

BW_b - data bandwidth, taken as twice the bit rate.

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Before entering into the system design, typical transmitter receiver design, and seeing the block diagram of transceiver for FHSS, let us understand some of the terms of it. Number one is the hopping range; it is a very important term usually the hopping frequency range signifies the difference of the lowest and the highest frequencies carrier frequencies getting utilized in the system. The hopping bandwidth correspondingly signifies the channel the bandwidth that is needed to pass this whole range of the hopping frequencies. Usually the hopping bandwidth will be denoted by W, and the bandwidth of the data modulation will be given by B into W b. See given a typical hop that bandwidth will be denoted modulation bandwidth will be denoted.

The receiver after synchronizing it will dehop the received signal. And hence after this de-hopping the signal that will be ending up with is called dehopped signal. The similar to the direct sequence spread spectrum system here also we will be interested to know what will be the definition of the processing gain. Remember the fundamentals of the spread spectrum communication system is that whenever you are spreading over a given bandwidth, then you will be always ending up with a kind of the processing gain associated with it. The processing gain here will be defined by the W divided by the bandwidth of the modulation, where W is the first null-to-null bandwidth of your available channel and B W b is the data bandwidth that is also taken as the twice of the bit rate.

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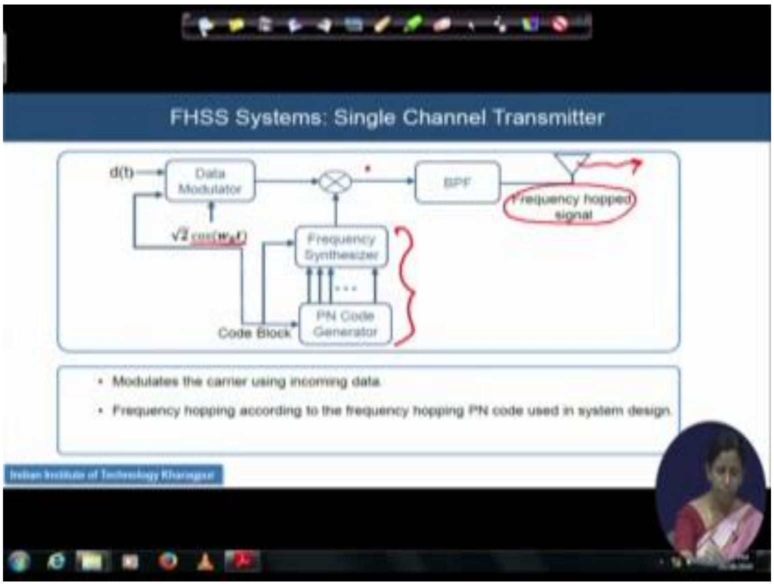

FHSS Systems: Single Channel Transmitter

- Modulates the carrier using incoming data.
- Frequency hopping according to the frequency hopping PN code used in system design.

Here we enter with the single channel transmitter design of FHSS system. As told here will be a single carrier which will be hopping over the available bandwidth. Here the carrier is given by cos omega naught t, and the incoming data stream the d t he is modulating the carrier frequency cos omega naught t. After data modulation is performed, here is the code generation circuit, where you are generating the PN codes that will help to hop this carrier over a wide range of the bandwidth available. The signal obtained here at this point is already the spread signal frequency hopped spread signal which is further passed to a band pass filter to give a shape a proper shape and to finally, form the frequency hop signal that will be transmitted via the antenna.

Remember in the whole system design, this code will be performing the key part of the design, which will be uniquely known to a specific kind of the transmitter and the intended receiver.

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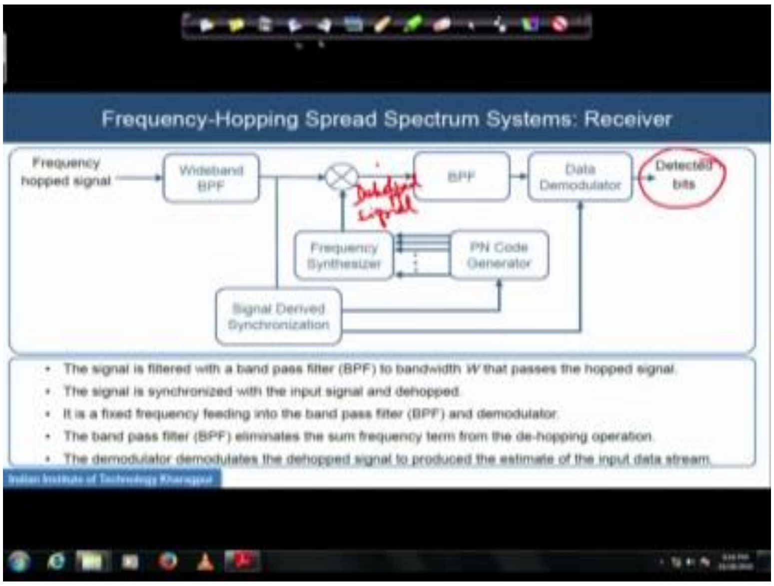

Frequency-Hopping Spread Spectrum Systems: Receiver

- The signal is filtered with a band pass filter (BPF) to bandwidth *W* that passes the hopped signal.
- The signal is synchronized with the input signal and dehopped.
- It is a fixed frequency feeding into the band pass filter (BPF) and demodulator.
- The band pass filter (BPF) eliminates the sum frequency term from the de-hopping operation.
- The demodulator demodulates the dehopped signal to produced the estimate of the input data stream.

Frequency hops spread spectrum receiver will be just to the on the other side where it will work like this. The hopped signal you have received from the antenna frontend which will be first required to be passed by the wideband band pass filter. He will capture the whole range of the hopped signal, which is equal to capital W that I have showed earlier. And if you are following a coherent system then you need to extract the synchronization information from the received signal, which is done in this block.

The synchronized signal is fed to the PN code generator and also is required to the data demodulation to keep a sync between the general code generation and the data modulation. The frequency synthesizer synthesizes the hopped center frequencies according to the PN code generated instruction. And this is a multiplexing unit who is who is helping us to dehop the signal with the generated locally generated PN sequence code. So, once you are here ending here you are getting the dehopped signal.

Remember this dehopped signal again we need to pass to a band pass filter because he will eliminate the sum frequency term from the de-hopping operation after this band pass filtering you are ready for the demodulation. And this synchronization information will help you to be in the sync of the code generation and the demodulation detected bits are obtained here. So, this is the overall structure, the way the frequency-hopping spread spectrum system works for the in the transmitter as well as in the receiver.

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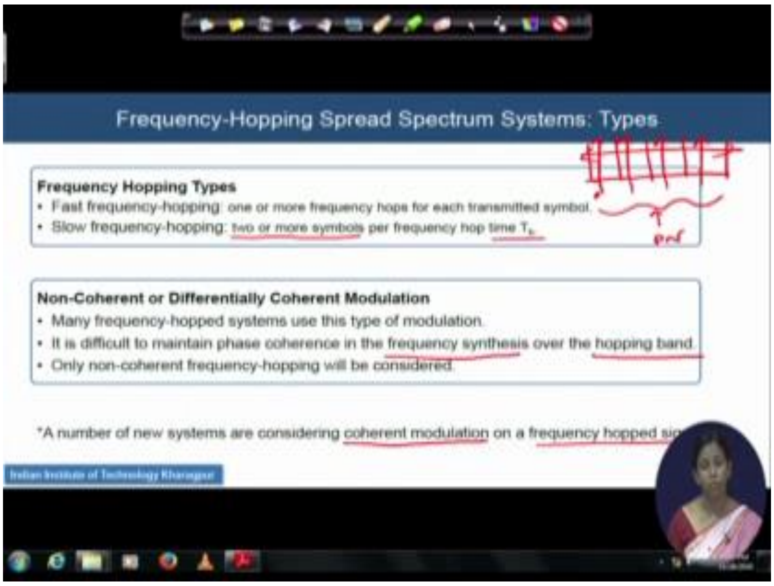

Frequency-Hopping Spread Spectrum Systems: Types

Frequency Hopping Types

- Fast frequency-hopping: one or more frequency hops for each transmitted symbol.
- Slow frequency-hopping: two or more symbols per frequency hop time T_c.

Non-Coherent or Differentially Coherent Modulation

- Many frequency-hopped systems use this type of modulation.
- It is difficult to maintain phase coherence in the frequency synthesis over the hopping band.
- Only non-coherent frequency-hopping will be considered.

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Now, coming to the types of frequency-hopping spread spectrum systems, so there are basically two types based on the rate at which you are hopping we call it a fast frequency-hopping signal hopping system or a slow frequency-hopping system. The slow frequency-hopping system I would like to mention first where the slow frequency-hopping system you will be getting two or more number of the symbols per frequency hop time. So, I should remember I should tell here, what is the hop time is. Suppose we started with these diagrams, we had a wide bandwidth W which we divided by number of the channels. And my center carrier frequency is hopping over this different channel based on certain pattern what will be the hopping pattern that will be governed by my PN sequence.

But what is the hop time is the duration between which the carrier frequency will be hopping from one channel to the next channel. So, it is basically the time that it is spending within a channel before hopping to the next. So, white is this slow frequency is if I think that for two or more number of the symbols that I am transmitting from transmitter to receiver, this hopping frequency is not changing then we call it is a slow frequency-hopping. On the contrary, for the fast frequency-hopping within a single transmission the carrier frequency may hop from one channel to the next.

Another one is the non-coherent or differentially coherent modulation techniques; it has a maximum popularity for the frequency-hopping spread spectrum system communication system design because of the so many reasons. As we understand that for coherent modulation scheme, we need to have a sync word associated with it which will help us to extract the phase time and frequency information in the receiver. So, it is an extra burden to us in the receiver and sometimes it becomes a extra hurdle for us to extract the information correctly so that the de-hopping operation can be done perfectly in the receiver.

To avoid all that people have preferred the non-coherent kind of the modulation scheme for this frequency-hopping spread spectrum system design. It is very hard the main difficulty comes from the maintenance of this phase coherence in the frequency synthesis and over the different hopping bands involved. However, for there are several new systems coming up where the coherent modulation is considered over the frequency-hopped signal.

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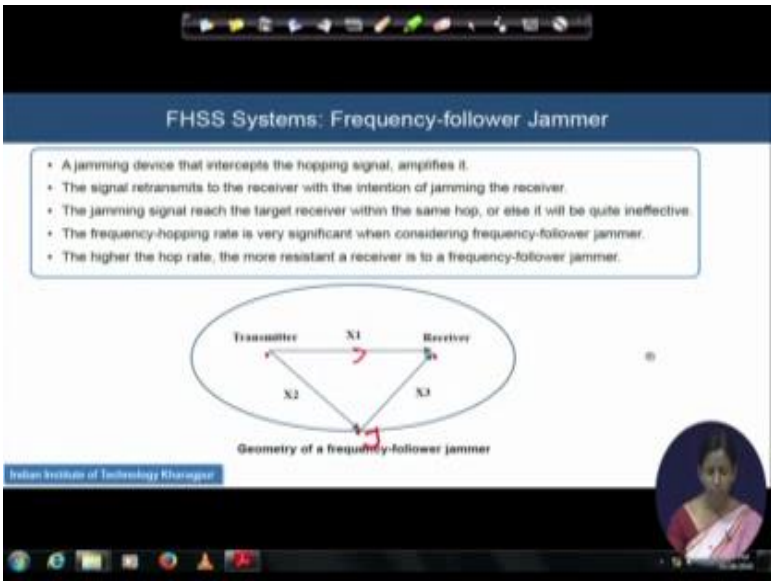

FHSS Systems: Frequency-follower Jammer

- A jamming device that intercepts the hopping signal, amplifies it.
- The signal retransmits to the receiver with the intention of jamming the receiver.
- The jamming signal reach the target receiver within the same hop, or else it will be quite ineffective.
- The frequency-hopping rate is very significant when considering frequency-follower jammer.
- The higher the hop rate, the more resistant a receiver is to a frequency-follower jammer.

Geometry of a frequency-follower jammer

In a frequency-hopping spread spectrum system, in context of the jammers, there is a very important concept of the rate of the hopping. How is it coming into the picture is something like this. Suppose, let us consider this situation where we have a transmitter transmitting and here is my intended receiver who will be receiving and however this is a location where my jammer is sitting and as it is in wireless communication. So, jammer is in the range of this transmitter and he can hear whatever is getting transmitted on air.

The jamming device it can intersect the hopping signal, it ties amplifies the received signal and he again retransmit it, so that actually it reaches to the receiver.

Think of a situation, if jammer the jamming signal can reach in the receiver exactly within the duration where actually the transmitter's signal is you see getting received through the path of x 1. Then you are in trouble because the jamming power is much higher than the power that is transmitted from the transmitter and basically getting received by the receiver through this direct path. So, your intended signal will be completely buried by the jamming signal, and you cannot be able to receive retrieve your own signal in the detection process.

Now, in with respect to a jammer to be a successful jammer, what you need to do is for an efficient jamming you have to reach in the receiver within the same hop, where actually the transmitter signal is transmitting. For such kind of the jammers, we call it is a frequency follower jammer and the underlying assumption is that the jammer could crack the PN sequence code that you are using to hop in the transmitter. So, he can also hop in the same pattern like you, so you are in trouble. And additionally if he can reach you within the same hop your detection process will be in high trouble because his transmitted power jamming power will be higher than your transmitting power.

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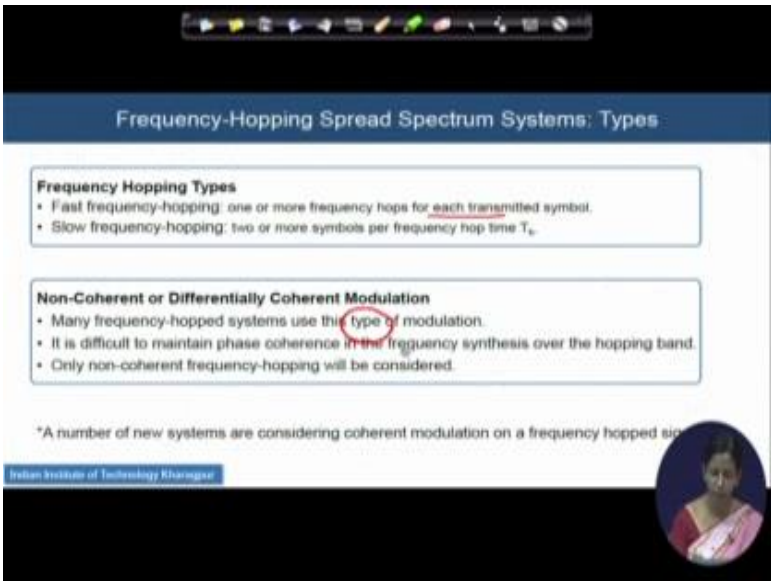

Frequency-Hopping Spread Spectrum Systems: Types

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Now, let us see little bit what will be the typical boundary zone within which actually the jamming signal will be really very, very effective with respect to the receiver detection.

So, we from the figure, we understand that the signal that is traversing from the jammer is following the path x 2 plus x 3. And there is another time involved inside the jammer which is called the processing time which is basically taken for the amplifying of the signal. So, to become a effective and following jammer frequency following jammer, what is required is see you need to do traverse like this I mean your jamming path is going via x 2 to x 3 and this is your intended transmitting to receiving path.

So, the equation should be something like this. Your x 2 plus x 3 divided by c this is the time taken by the signal to travel via the jammer. This is the extra processing time that the signal is getting processed getting amplified inside the jammer. And x 1 by c is the direct path between the transmitter to receiver signal is taking this much time to receive from transmitter to receiver. And what is this extra term we are introducing is this is the hopping time that carrier is hopping between channel to channel in the receiver. And alpha is the extra fraction of the time that actually when the hop is in the hop there is no hit, hit means within that you have you could not reach, basically 1 minus alpha into the processing time that into the time that will be the heat sorry it will be T h. So, it will be there will be a hit.

So, once actually you are hitting the time, so, the total time you are elapsing in the jamming path that should be if it is less than equal to this alpha T h plus x one by c then this is the effective jamming, it could be you should be able to succeed in jamming the whole stuff.

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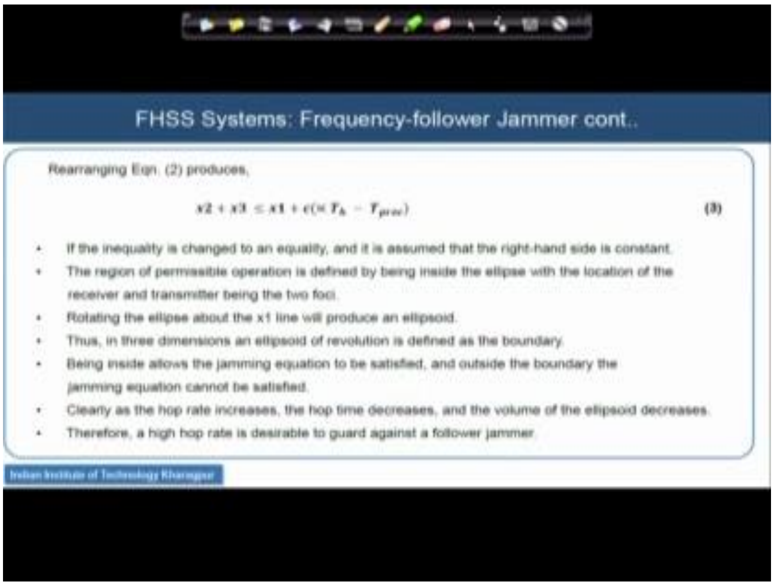

FHSS Systems: Frequency-follower Jammer cont..

Rearranging Eqn. (2) produces,

$$x2 + x3 \le x1 + c(\alpha T_h - T_{proc}) \quad (3)$$

- If the inequality is changed to an equality, and it is assumed that the right-hand side is constant.
- The region of permissible operation is defined by being inside the ellipse with the location of the receiver and transmitter being the two foci.
- Rotating the ellipse about the x1 line will produce an ellipsoid.
- Thus, in three dimensions an ellipsoid of revolution is defined as the boundary.
- Being inside allows the jamming equation to be satisfied, and outside the boundary the jamming equation cannot be satisfied.
- Clearly as the hop rate increases, the hop time decreases, and the volume of the ellipsoid decreases.
- Therefore, a high hop rate is desirable to guard against a follower jammer.

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Now, if we rearrange the last equation, we will be ending up with this x 2 plus x 3, it should be less than equal to x 1 plus c into alpha T h minus T proceeding as is shown in the equation number 3. And if I in the right-hand side if we change this inequality equal to the in the equal sign on the side basically what we are ending up with is this region of the permission operation of the jamming is basically being inside an ellipse. What is shown in this figure where transmitter is one focus of the ellipse and receiver will be the another focus of the ellipse. And if we turn the ellipse with respect to the x 1 axis, it will form an ellipsoid and this ellipsoid will basically give you the boundary of the jamming zone.

So, in order to be a successful jammer, you have to be within this jamming boundary. Obviously, so if I am reducing the T h I mean the time of hopping; that means, your rate of hopping is increasing then; obviously, the total area under the ellipsoid that will be deceasing. So, that will be your target area as a system engineer you try to decrease the boundary zone and the total area under the ellipsoid, so that actually your receiver can be resistant against the jammers.

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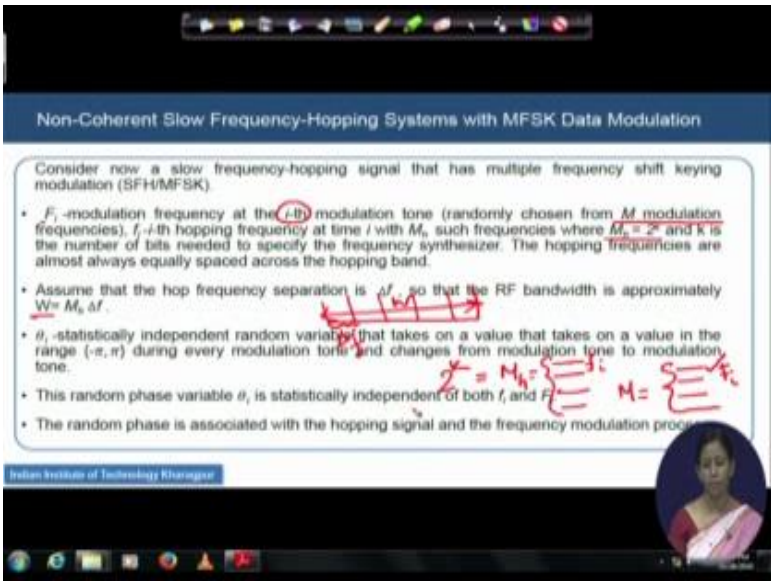

Non-Coherent Slow Frequency-Hopping Systems with MFSK Data Modulation

Consider now a slow frequency-hopping signal that has multiple frequency shift keying modulation (SFH/MFSK).

- F_i -modulation frequency at the i-th modulation tone (randomly chosen from M modulation frequencies). f_i -i-th hopping frequency at time i with M_h such frequencies where $M_h = 2^k$ and k is the number of bits needed to specify the frequency synthesizer. The hopping frequencies are almost always equally spaced across the hopping band.
- Assume that the hop frequency separation is Δf, so that the RF bandwidth is approximately $W = M_h \Delta f$.
- θ_i -statistically independent random variable that takes on a value that takes on a value in the range $(-\pi, \pi)$ during every modulation tone and changes from modulation tone to modulation tone.
- This random phase variable θ_i is statistically independent of both f_i and F_i
- The random phase is associated with the hopping signal and the frequency modulation proc

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Few more considerations and now we will enter slowly inside a understanding of MFSK data with a MFSK data modulation, how the frequency-hopping spread spectrum system would look like. Let us consider that capital F i is the modulation frequency. And this modulation frequency is in the i th modulation; at the i th modulation tone. Remember we are choosing the i th modulation tone from a set which is having capital M number of the modulation frequencies. So, it is something like that. I have a set of the modulation frequencies as it is a frequency shift keying, so I may have suppose four different set S h which is having a four different frequencies to select for the modulation for the data modulation basically.

And there is another set which we are calling as M h which is actually talking about the how many number of the hopping frequency set you are having. So, for at i th time, I will have a choice of any one data modulation frequency which I will call as capital F i; and for this capital F i, I will choose a another set of the hopping frequency from this set which I will call as small f i.

Remember that for a typical modulation data modulation, I may select multiple if it is a fast frequency-hopping, multiple hopping frequency and otherwise if for a multiple number of the modulation data modulation, I can actually choose a single hopping frequency which will be a slow frequency-hopping system design in that case. And this capital M h which is having a quick relation with the number of the bits that you are taking for the frequency synthesizer design is generating the code of this hopping and this capital m h is a hence can be written as 2 to the power k.

So, for example, if I have a 3- bit frequency synthesizer, I can generate 8 different set of the frequencies for hopping correspondingly I have 8 channels over which my carrier can hop. Remember if I am having a total bandwidth of W with which I started. So, now, this whole W will be a basically my M h into del f; M h is what? M h is the number of the center frequencies which are available for my hopping. And del f is the difference between that center frequency, so it is basically this guy del f which is telling the difference between one center frequency to the next. So, the total bandwidth hence this W can be now written in terms of the number of the hopping frequency available, and the frequency gap you are having between two corresponding hopping frequencies.

Theta i is a random phase variable that is that will inheritably will be added and it is statistically independent for both this small f i and the capital F i, this random phase will be automatically associated with the generation of the hopping signal and the frequency modulation process. So, we will be next slide we will be handling with capital F i small f i, capital m, capital M h, the bandwidth W and this independent phase component theta i to show you the modulated and transmitted frequency hopped signal.

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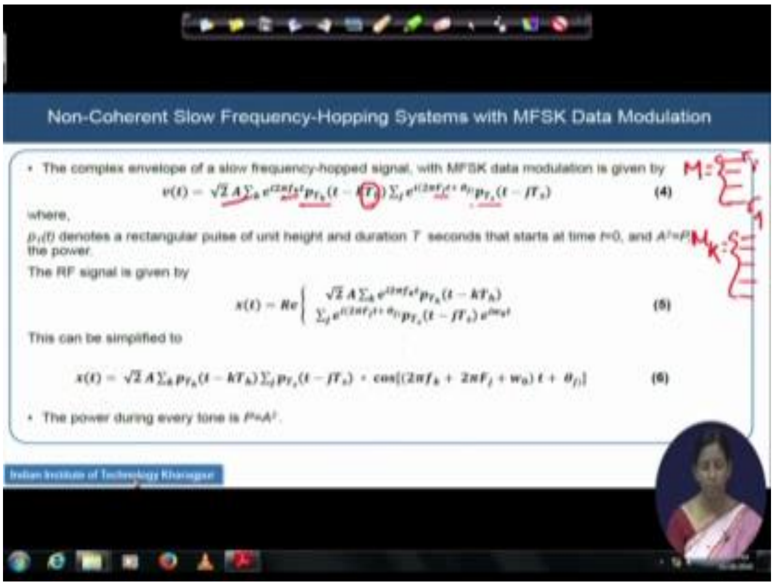

Non-Coherent Slow Frequency-Hopping Systems with MFSK Data Modulation

- The complex envelope of a slow frequency-hopped signal, with MFSK data modulation is given by

$$v(t) = \sqrt{2}\,A\sum_k e^{j2\pi f_k t} p_{T_h}(t - kT_h) \sum_j e^{j(2\pi F_j t + \theta_j)} p_{T_s}(t - jT_s) \quad (4)$$

where,

$p_T(t)$ denotes a rectangular pulse of unit height and duration T seconds that starts at time $t=0$, and $A^2=P$ the power.

The RF signal is given by

$$x(t) = Re\left\{ \begin{array}{l} \sqrt{2}\,A\sum_k e^{j2\pi f_k t} p_{T_h}(t - kT_h) \\ \sum_j e^{j(2\pi F_j t + \theta_j)} p_{T_s}(t - jT_s)\, e^{jw_0 t} \end{array} \right. \quad (5)$$

This can be simplified to

$$x(t) = \sqrt{2}\,A\sum_k p_{T_h}(t - kT_h) \sum_j p_{T_s}(t - jT_s) \cdot \cos[(2\pi f_k + 2\pi F_j + w_0)\,t + \theta_j] \quad (6)$$

- The power during every tone is $P=A^2$.

Thus we are considering a slow frequency-hopping signal. So, let us start with it we chose the data modulation frequency F j. So, I wrote that j can vary any value and j can and I have a capital set M from which I am choosing this F j. So, if j is equal to four. So, i will have F 1, F 2 F 3 and F 4, capital F 1 to capital F 4 to choose. Theta t is the random phase associated with it. Like in direct sequence spread spectrum system here also we are having a pulse rectangular pulse will be transmitted and which is having an unit height.

The duration of that pulse is equal to capital T second. And the pulse is starting the time will be t 0 and hence a will be the s square is the power of the transmitted signal p T h is the pulse rectangular pulse associated with your hopping pattern and T h is equal to your hopping time. Small f k you have chosen from your M h or M k here and you are having a several set of the hopping frequencies that you are choosing. And small k here is denoting here how many number of the such frequencies you are having in your data bank.

So, this is the total transmitted signal you could see hop transmitted signal. Basically we will see this is the product of the complex envelope of the data modulation getting multiplied with the complex envelope of the frequency-hopping. The r f signal of it will be simply the real part of this whole section. And if we are expanding this exponential term here, we will be ending up with only the cos term in the equation shown in the equation 6 and this will be the simplified for x t is the simplified form of the transmitted signal.

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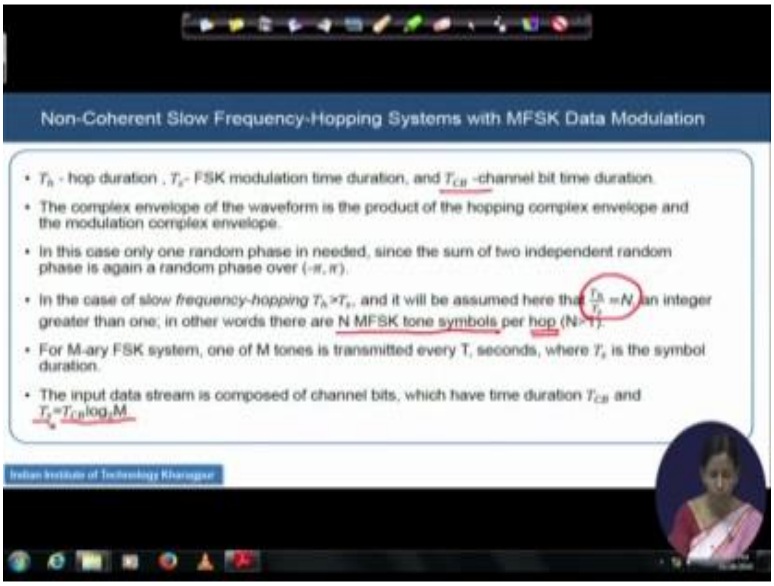

Non-Coherent Slow Frequency-Hopping Systems with MFSK Data Modulation

- T_h - hop duration , T_s- FSK modulation time duration, and T_{CB} -channel bit time duration.
- The complex envelope of the waveform is the product of the hopping complex envelope and the modulation complex envelope.
- In this case only one random phase in needed, since the sum of two independent random phase is again a random phase over $(-\pi, \pi)$.
- In the case of slow *frequency-hopping* $T_h > T_s$, and it will be assumed here that $\frac{T_h}{T_s} = N$, an integer greater than one; in other words there are N MFSK tone symbols per hop (N>1).
- For M-ary FSK system, one of M tones is transmitted every T_s seconds, where T_s is the symbol duration.
- The input data stream is composed of channel bits, which have time duration T_{CB} and $T_s = T_{CB}\log_2 M$.

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So, T h was our hop duration, T s is the frequency modulation time duration to us. And if this is the channel bit time duration, so we have already seen in the last slide that the transmitted real the simplified form of the transmitted data symbol will be a combination of this T h and the T s. Remember there is a nice relation between this T h and T s if it is a slow frequency-hopping will get integer number if I divide the T h with the T s. And it is basically taking telling the how many number of the MFSK symbols are getting you are transmitting per hop. Input data stream here will be composed of the channel bits and the channel bits will be given the relation between the channel bit duration and the symbol duration is as usual will be given by this T s equal to T C B log M to the base 2.

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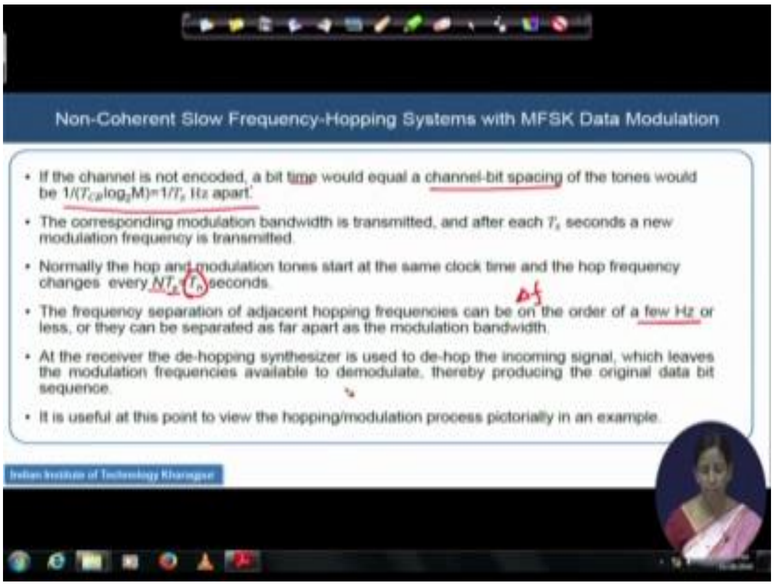

Non-Coherent Slow Frequency-Hopping Systems with MFSK Data Modulation

- If the channel is not encoded, a bit time would equal a channel-bit spacing of the tones would be $1/(T_{CB}\log_2 M) = 1/T_s$ Hz apart.
- The corresponding modulation bandwidth is transmitted, and after each T_s seconds a new modulation frequency is transmitted.
- Normally the hop and modulation tones start at the same clock time and the hop frequency changes every $NT_s = T_h$ seconds.
- The frequency separation of adjacent hopping frequencies can be on the order of a few Hz or less, or they can be separated as far apart as the modulation bandwidth.
- At the receiver the de-hopping synthesizer is used to de-hop the incoming signal, which leaves the modulation frequencies available to demodulate, thereby producing the original data bit sequence.
- It is useful at this point to view the hopping/modulation process pictorially in an example.

With all that understanding, and if the channel bits are not coded we can understand that the bit time will be simply equal to the channel bits spacing as the coding is not involved and hence we can write this equation. Now, fundamentally we are ending up with a understanding that if we are given the T h number, T h seconds for hopping and we have the N number of the MFSK tone symbols to be transmitted, each of the symbol is having a duration of this T s. So, definitely N into T s will construct the hopping duration T h.

And the difference the frequency separation del f that we have discussed earlier between two adjacent hopping frequency can be very few hertz and it can be a very large for far apart signals far apart center figure frequencies, it will be even several kilo hertz also. At the receiver, these de-hopping synthesizers will be used to de-hop the signals as I have shown earlier in the receiver design and using that whole concept and we will be now seeing a very nice hopping modulation process with a nice example in the next session.