**Indian Institute of Technology Kanpur**

**National Programme on Technology Enhanced Learning (NPTEL)**

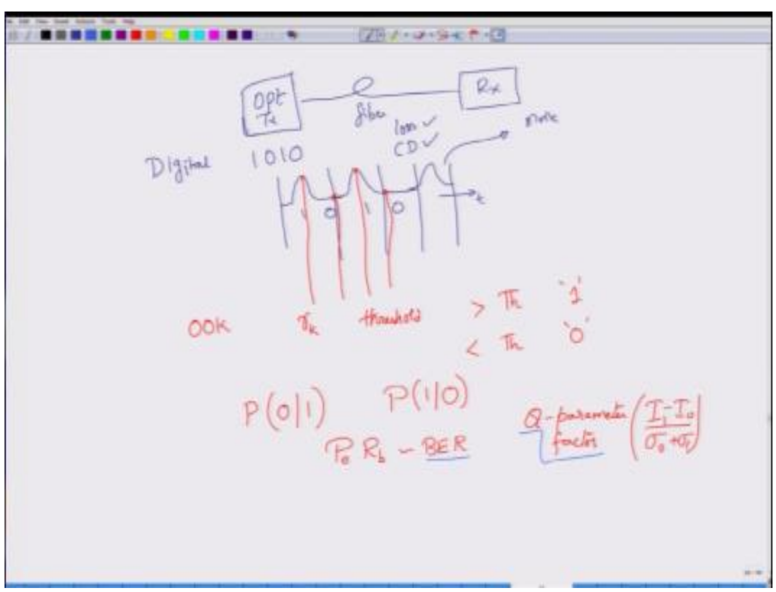
**Course Title**
**Optical Communications**

**Week – XI**
**Module-III**
**Eye diagram & Higher modulation techniques**

**by**
**Prof. Pradeep Kumar K**
**Dept. of Electrical Engineering**
**IIT Kanpur**

Hello and welcome to the mook on optical communications. In this module we will first look at eye diagrams which is one of the visual ways of talking about the performance of an optical communication link. And then talk about higher order modulation or spectral efficient modulation techniques which are going to increase the spectral efficiency of the current optical communication systems. Before that let us look at the eye diagram as I said okay. So we have already seen how to characterize the performance of an optical link.

(Refer Slide Time: 00:47)



Suppose you have an optical transmitter okay which is sending out a sequence of bits, so let us call this as 1010 and so on okay, I am assuming that we are looking at the digital optical links for an analog optical link the performance measure that we are going to describe what is called as eye diagram does not really apply. For an analog communication link the performance is usually quantified by the signal to noise ratio and if you have transmitted a certain wave form the fertility of the system that is how good the system is, is described by how less noisy and how you are able to reproduce the wave form at the receiver.

So this eye diagram is something that is used only for digital communication systems, for mostly for digital communication systems and we are going to look at what this eye diagram is. So you are going to transmit this optical, you know signal which are modulated 1010 by, you know by whatever the bit pattern that you have. Now when the signals go through a fiber right, we already know that fiber introduces loss which means that the amplitude of the signal starts to reduce.

As well as introduces chromatic dispersion, the fiber chromatic dispersion causes the optical pulses to spread out causing an inter symbol interference. So at the transmitter you might actually have a nice symbol okay, this is corresponding to 1 this is 0 and then you have a 1 again and then you have a 0 and so on okay. So these symbols are very nice in time okay which are very clean, no noise, no going outside the allotted bit interval or a bit slot.

So these are, no for example the bit boundaries that one can assume, these bit boundaries slightly gone in the other side, but it is okay, you can kind of understand what I am trying to convey over here. However, once you get this wave form at the receiver side after your photo detected you would have noise in addition to loss as well as chromatic dispersion.

Loss you have somehow overcome by putting an optical amplifier, chromatic dispersion can be compensated, but if it is not compensated, then it will also show up in the final result. Noise of course would always be present, no matter what you do, noise cannot be completely eliminated from the received wave form. And you are, you know as you know how do we interpret the digital signals.

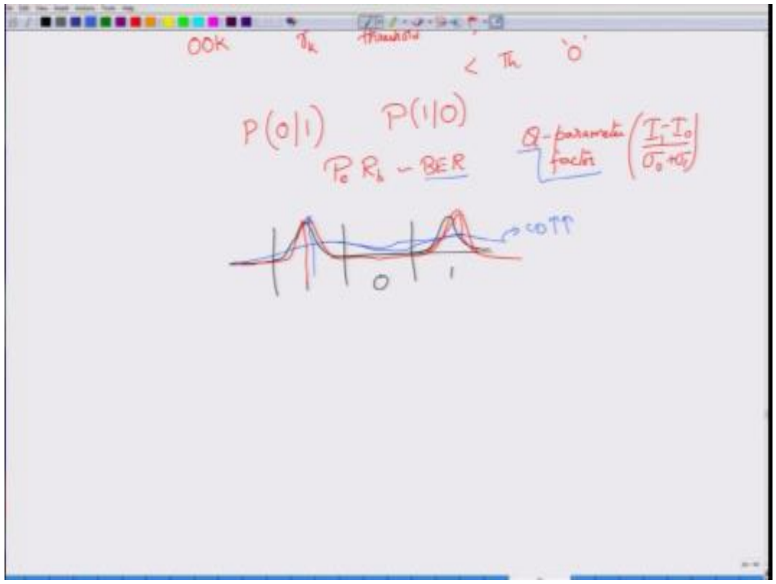
So at the receiver side what we do is, we actually sample this signal right. So we actually sample the signal value and subject this sample value in order to a, so we sample this one generating the signal sample let us call this as $R_k$ and then subject these received samples $R_k$ to some kind of a threshold detection right. So if you assume that you are working with a simple on-off keying system in which a bit 1 is represented by a presence of a pulse and 0 represented by no pulse, then if the value of the sample signal which of course will be the original signal plus there will be some noise.

If it is greater than a certain threshold then you declare the bit as 1, if it is less than the threshold then you declare a bit as 0 okay. In the case of a die of course, it is possible that you simply allocate the detection to either 1 or 0 does not really matter and how frequently you are going to errors right so when you have actually transmitted a bit 1 but you interpret the result has a 0 we had actually calculated what is the probability of this happening correct we had also calculate the probability of mistaking a 0 into a 1 these where know as conditional probabilities and combined with the probability of transmitting a 0 and 1 we obtained expression for what is called as probability of error.

So this probability error multiplied by the bit rate is what we called as the bit error rate in order to talk about bit error rate we also introduced another parameter called as Q parameter or the quality factor okay so we talk about Q as a Q factor which basically measures you know some sort of margin between the photo current that is the difference between the photo current when the bit 1 transmitted and photo current when bit 0 transmitted to the noise that exits in the system okay.

So $\sigma_0$ and $\sigma 1$ are the RMS values of the noise current when we have transmitted bit 0 and bit 1 respectively so we have B here as the performance measure we have looked at Q factor as a performance measure but these measurements do not tell you anything you know they do not give you a graphical view what is happening to the system more over they are also not going to tell you what is the permissible sampling error time that I have okay so if the chromatic dispersion is pretty lager then the received pulses will start t behave very strangely.

(Refer Slide Time: 05:42)

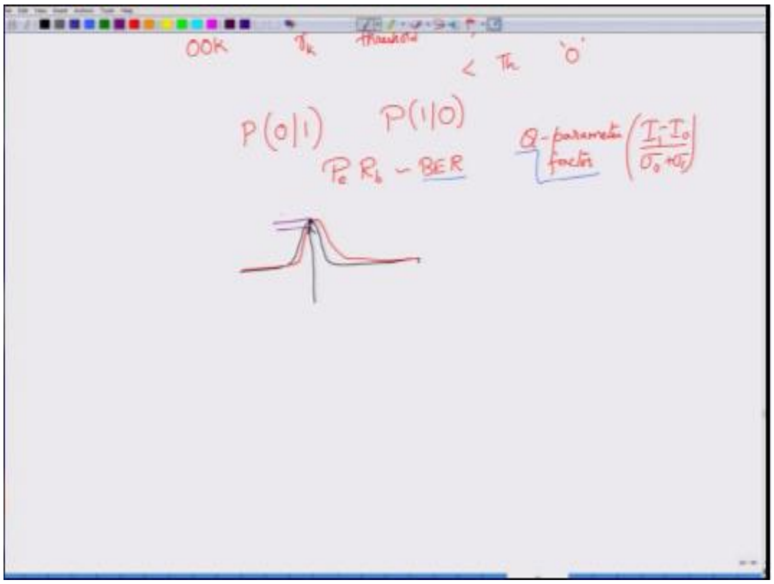



So let us say these are my original bit boundaries and I have a pulse okay this is 1, this is 0 so this is bit 1 this is bit 0 and then I have one more pulse okay so this corresponds to bit when the chromatic dispersion is very then what happens is that the signal would almost be flat okay so the signal would almost be flat in the sense that it would it would be spread out quite a bit and then in the slot of 0 you might actually see something okay.

So this would be the situation when the chromatic dispersion is very large however this does not enter into the BER or the Q factor not at least until you make some additional modifications the expressions for BR or the Q factor so to analyze the effects of chromatic dispersion on the pulse okay what is the rise time of the pulse with 1 and 0 are transmission from 1 to 0 and 0 to 1 transient when you have chromatic dispersion also when you have noise and whether all these symbols are coming in at their corresponding bit boundaries for example in one tine you have this particular bit boundary signals are arriving within that next teem there might be a small delay okay.

So you might not have a large amount of chromatic dispersion but then you have a mall delay okay that should have been just a small delay out there and you might also have situation where this delay can be either earlier or later okay this will be a very important factor because earlier you are sampling at the maximum point okay now because of this error or the glitter in the arrival.

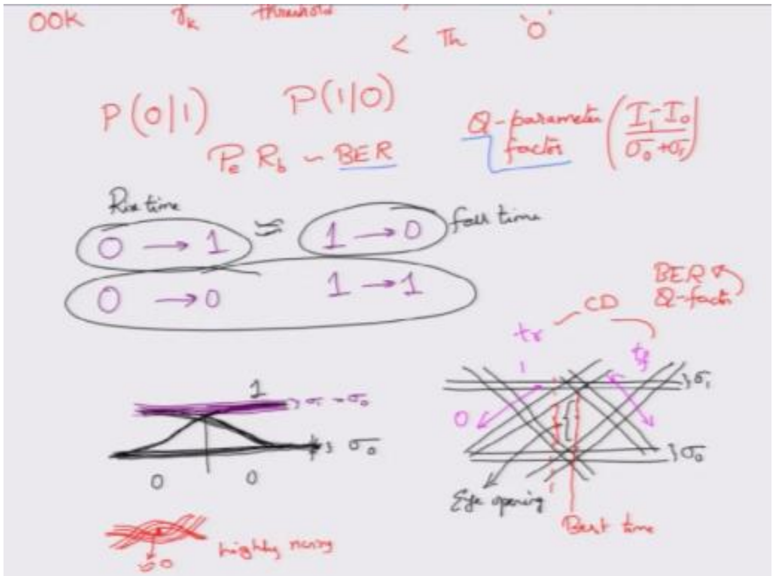
(Refer Slide Time: 07:18)




So you are sample voltage what you have will actually be less for example let us say this is the point where we sampling originally. So this is my original sampling point now because of the delay you know are the glitter which is random the signal did not arrive at this point but rather the signal peak occurs after some time but my sampling time is still the same right and what would be the sampling value that would be this blue color one if you look at the difference right there is actually a difference between the blue dot and the black dot.

And this difference that I would have when there was no sampling error has now been reduced it is not that current as decreased in amplitude the current peaks simply occurs at a later time, you can very well see that if the peak occurs at an earlier time also you will lose a little bit of a current value out there, right. So the Q-factor will slightly reduced, all this information is captured by what is called as the eye-pattern of the system.

(Refer Slide Time: 08:19)




In the eye pattern of the system or of the link what we do is, we send in sequence of waveforms okay so we send in a sequence of bits and we look for four transitions because this is an ON-OFF keying we look for four transitions one is 0 to 1 and you have 0 to 0 transition you have 1 to 0 transition and 1 to 1 transitions, okay. These transition which are at the lower side which is 0 to 0 and 1 to 1 so not really tell you much except that they tell you.

How much noise exists okay and the transition from 0 to 1 usually gives you the rise time of the system and the transition from 1 to 0 will give you the fall time of the system usually these two are equal to each other but they may not be equal in an actual scenario, okay. So an eye diagram actually captures that, what we do is we look for 0 to 0 transition which you know like from 1 we take one but boundary at the middle.

So this one is one symbol and this one the next symbol we take these two symbols and start overlapping the signals okay we start overlapping the signals like this okay you can see that the 0 value is not exactly 0 right there is actually a small width within which you are able to get any signal so even though you have transmitted a bit 0 and the next bit also 0 there is a certain amount of change in the amount of the current eye 0 value that you are going to get even when you are transmitting only 0 and 0 and this of course will be the RMS value of the noise that would be added when you have transmitted a bit 0.

Now consider what happens when you have a 0 to 1 transition, okay. So let us say this is the 0 to 1 transition and this is actually already not a very good transition that we have okay, so you have this 0 to 1 transitions if you have the present waveform is 0 or the present symbol has 0 the next symbol has 1 those transitions are again know matched in this way you will also have a 1 to 1 transition.

Which is usually much more noisy than the 0 to 0 transition of course the reason is very well known to you the reason is because σ1 is larger than σ0, so because of σ1 being larger than σ0 this would be transition that you want to get, also you will have a 1 to 0 transition okay, so this would be the 1 to 0 transition that we have, okay. So hopefully this is all symmetric or atleast you should be looking symmetric to you, okay.

So this particular diagram that we have is what is called as the eye diagram, okay but normally you do not put the eye diagram in this way you just kind of shifted slightly okay, so in the sense you look at two transitions so that you get a nice wave out like this okay so this is 0 to 0 transition, this is 1 to 1 transition and these slopping lines are 0 to 1 a d 1 to 0 transitions, okay again the diagram is slightly off but look at the text book that we are you know that we were looking at in the course.

And as I said this will tell you the noise limit for 0 this will tell you the noise limit for 1 and w2hat you see here this should have been more symmetric let me try and make it more symmetric over here, so this should have been the symmetric point, okay. So if you look at this way this is called as the eye opening okay, eye opening tells you how much noise margin that exists in this particular link, okay.

If the eye opening is small then it mean that the system is very noisy, okay. If the eye opening is large then the effect of noise is very small also the slope of these lines that you have will tell you the transition from 0 to 1 or will give you the raise time the slopes of these lines which are going from 1 to 0 will give you the fall time, raise time and fall time are usually the same, if there are any other imperfections.

For example, if there is a transition from 0 to 1 but because of a low pass nature you know some times or there is a certain capacity element in the amplifier you might actually see an over shoot, okay and you might also see an under shoot so all these effects are captured by the eye diagram, okay. The best time to sample is right in the middle when the eye is maximum okay, so this is the best time to sample why, because you get the largest margin over here.

If you decide to sample somewhere over here the amount of margin that you are going to get with signal to noise is much smaller than the corresponding noise margin that you are going to get, okay. In a particularly bad scenario you might actually have a situation where the noise is such that the eye is barely opened, okay so you might actually see that this is the eye opening and this eye opening is almost equal to 0 indicating that the system is highly noisy, okay.

If this slope by measuring the raise time of this one of this slope from the transition on 0 to 1 it is possible to link both raise time as well as fall time if you measure it, it is possible to find out how much the chromatic dispersion that existed so if you know what is the raise time of the pulse before propagating through the fiber then you can look at what would be the situation after it has propagating the fiber and from there estimate what is the chromatic dispersion, okay.

It is also possible to estimate the BER as well as the Q factor of course Q factor is simply this margin that you are going to get, from the Q factor you can go back and measure BER. So the additional advantage of having eye diagram information is that it is possible to extract the non visual performance matrix, that is Q factor and BER both from the eye diagram. So let us stop our discussion of the eye diagram over here, okay and then look at the next topic which you know hopefully promises lot more fun than what has been so far, okay.

One of the things that we talked about, right when we went from the RF systems or the wireless systems or the copper cables from those systems we went to the optical communication systems starting in 1970s and today virtually all of the communication except for some satellite communication, okay and under water very specialized communications happens more or less by optical means even the wireless based stations are linked by fiber optic cables, fiber optic networks so that only the mobile part that is your hand set to the base station communication and hand set to hand set communication happens over a wireless channel or such as an atmosphere or in air.

But even with the almost infinite band width you know or the enormous bandwidth that the optical fiber offers currently, right the demand for traffic as more and more people get interconnected to essentially internet and start using this highly demanding applications such as video on demand you know or downloading movies, uploading large data files, okay so when these activities happen even the supposedly large capacity optical network comes under lot of stress, okay.

And this has been particularly you know experienced over the last decade that the demand for bandwidth is going up and up unless we actually take care of you know upgrading the mechanisms of optical communication systems then it would not be possible for us to meet the increasing demands.

Of course people are always looking forward in the future and about 15 years ago developments actually started towards a next generation, remember in the first few generations your data rates were very small then came the 2.5GBPS standard with the help of optical amplifier and WDM revolution with push the data rate from 2.5 to 10 GBPS and there was an inter mediate 40GPBS upgrade.

Now the current technology is actually at 100GPBS okay, so we are now able to send over 1 wave length or at least you know very small band as I would call we are able to send about 100 GPBS update and over a DWDM system which consist of about 200 channels at a same time you are able to send more than terabits per second data okay, so this large data should data rate one would think should be sufficient but unfortunately it is not is going to be further increased okay.

However what technology is have actually gone from for you know for us to go from simple on off keying 10GPBS and of course saying simple only in the relative contest okay even the 10GPBS system is not very simple lot of system improvements had to be put ion to get to2.5 to 10 GPBS but from 10 GPBS to 100 GPBS has been a real challenge and people have met this challenge by you know coming up with what is called as spectrally efficient modulation techniques okay, this seems to be a very fancy word but the simplicity of this scheme is that in the on off keying system you actually used only the intensity of the signals.

You know if the pulse was present you had a bit one if the pulse was absent you had a bit 0 however we never modulated the phase of the optical carrier and to go from 10 to 100 GPBS people did exactly that so they went from simple on off keying modulation to complicated slightly complicated in terms of the modulation technology in to what is called as BPSK transmission we have already looked at QPSK in the earlier modules we will simply very quickly review all those thing okay.

And not satisfied with BPSK people went further up okay you now have BPSK in which 8 phase states are created at a particular intensity level. Then came the 16 QAM which could be constructed in many, many ways you have the star quam and you have the square QAM okay, from there people went onto 64 QAM and that seems to be the sealing currently with coherent optical systems.

Now only at the transmitter side was not the revolution that happened I mean after all you could always do the phase modulation even you know 20 years ago but the real revolution lied in the receiver side because in modulating the phase you are in coding information in the phase of an optical carrier and there exist no method to directly tell you what the phase of a simultaneously signal is you can actually try and do that one right there is no detection mechanism okay especially the photo detector cannot detect phase they are immune to phase what do they detect they only detect the modules square of the incoming optical signal.

So all the phase information is washed out however using the coherent detector which means constructing a local or oscillator you are able to extract the phase so you are able to convert t the phase fluctuations in to intensity fluctuations and by looking at those intensity fluctuations you are able to infer what bits or what symbols where transmitted however this also means that the local oscillator and the original signal that is being you know on the frequency they have to be sinker noised with each other right.

If this has a certain phase variants or the phase a noise variation then the local oscillator also has to track those phase variation so they have to be in phase with each other for coherent systems to work in the 90's concept was widely know but was not really applied, the main bottle neck there was the optical phase lock look, you could not really built optical phase lock loop with, which transmitter and receiver widely separated, and such that the constrains in optical phase lock loop was much more then constrain on the RF phase lock loop, okay.

So because of the n and the primary culprit of all that was the laser phase noise, so today we have brought down the laser phase noise, with a line width ranging from few hertz to about 100 khz, commercial systems, even with that lower phase noise it is still very difficult to implement the distributed optical phase lock loop, okay.

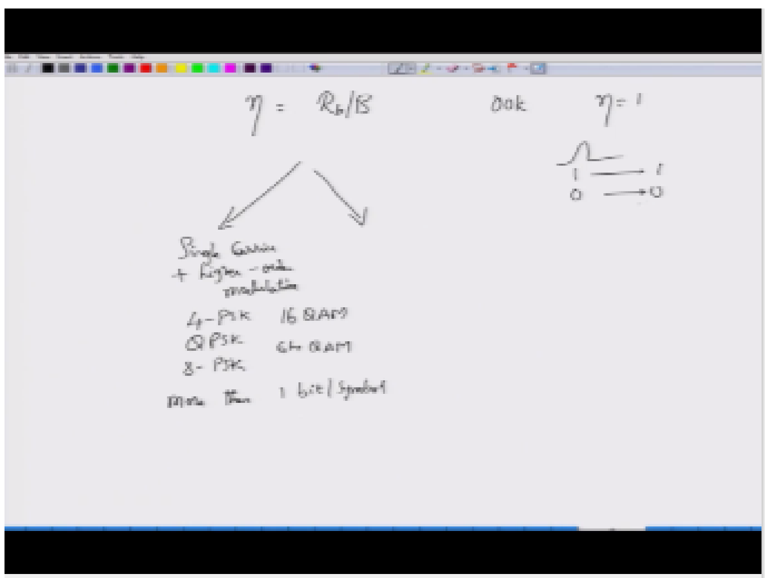
Rather than that, what people do is they let the local oscillator work on the coherently receiving the signals, whatever the phase imperfections that exists would now be mitigated using digital signal processing, while you are using digital signal processing to mitigate the phase, you can also, mitigate the phase the frequency of set, that is you received local oscillator frequency, if it is completely different from the transmit signal frequency, right.

And if this offset does not remain constant, but rather keeps changing, then you will lose performance, okay so the performance will suffer, even if the offset is constant then the performance is still suffers by about 3dp, as we will see in one of the exercises, so to obtain the best performance you have to keep the frequency offset equal to zero, again this topic I mean those topic is also done by or this task can be accomplished by digital signal processing.

Finally you can also compensate for the chromatic dispersion that exists in the fiber, not by going to the fiber based mechanisms but rather using DSP to perform all these tasks, okay with considerable use of DSP algorithms, it is now possible to transmit data at 100JBPS, and in the next module as we begin we are going to look, I mean in this ,module as we begin later we are going to look at some of those advanced modulation technologies, okay, and we will talk about what is the drawback of this system later on, okay.

How can we first improve the spectruatilization? We define spectral efficiency as the efficient utilization of the bandwidth, in terms of how many bits per second, or what is the bit rate to the bandwidth, that we have utilized, okay so with that let us jump in to look at some of the approaches that are taken in order to increase the spectral efficiency, okay.

(Refer Slide Time: 22:42)




So spectral efficiency is given by, the bit rate to the bandwidth that you have used, okay for a simple ON OFF keying this spectral efficiency is actually equal to 1, because the bit rate is so and so bits per second and it requires exactly the equal amount of bandwidth that you have looked at, there seems to be to increase the spectral efficiency there are two major approaches.

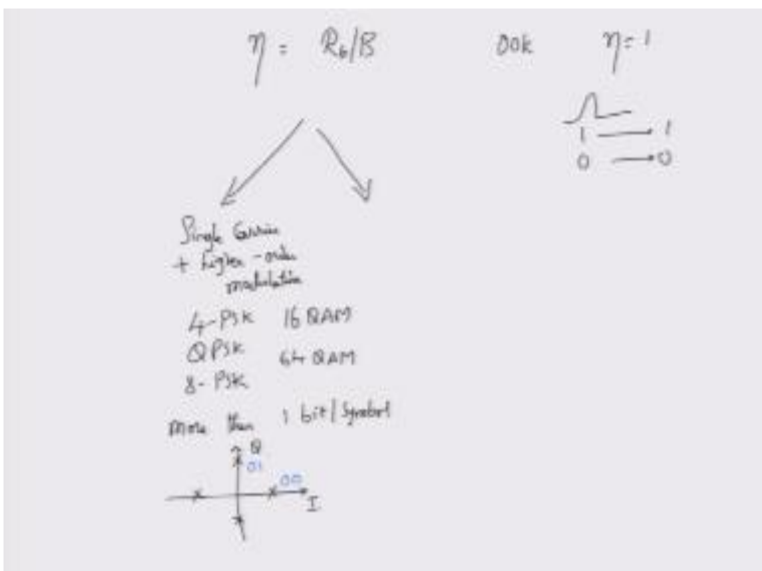
One is to use what is called as single carrier systems, but use higher order modulation okay, so with higher order modulation your basic modulation formats start with say BPSK, BPSK or

BPSK, or BPSK for short, if you have 16 QAMS and 64 QAM, okay all these higher modulation technologies what they do is, they try to assign more than 1 bit per symbol.

Recall your ON OFF, keying system, ON OFF keying system you should transmit 1 bit okay, so if the bit is one, the symbol that was transmitted was also 1, because the bit 1 to 1 here, if it was bit 0, then the symbol was also 0, so in this case each bit was mapping only one particular symbol with BPSK which we have discussed in one of thee earlier modules, you have options of 4 states, okay. 4 phase value this is the, I and Q axis of the system that we have looked at, so these points are called as the constellation points and the entire thing is called as constellation.

We have looked at all these in one of the earlier modules, with this 4 phase state for the BPSK; it is possible to associate 2 bits per symbol.

(Refer Slide Time: 24:37)

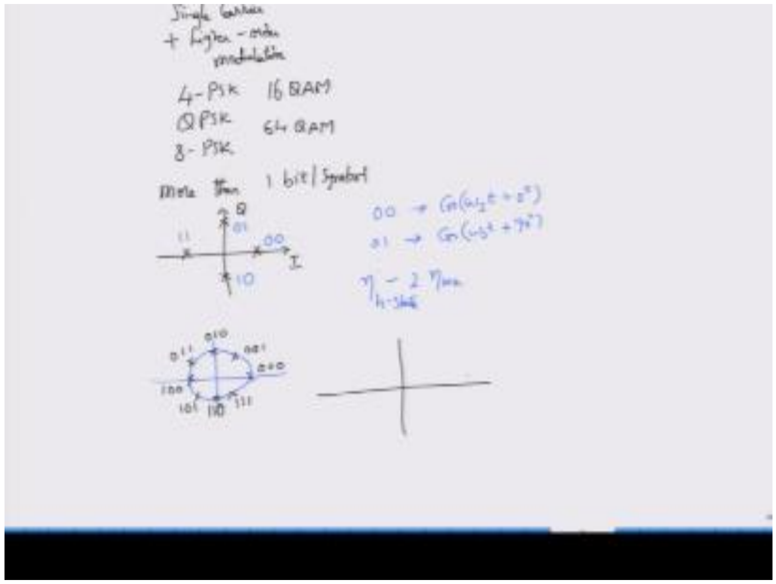



If you prefer a gray coded version, in which the two symbols you know are different only by one bit, this is the so called gray coding approach, okay. When you transmit phase 0 you are actually encoding that phase 0 by 2 bits, in another words if you are want to transmit 2 bits sequence 00, to transmit a signal which is say cosωst, where ωs is the signal frequency + 0 degrees. If you want to transmit 01, right? So you group 01 into 1 bit sequence then you transmit cosωst but this time shift the phase by 90 degree.

Similarly for the remaining two, so what has happen now is, the bit rate or the number bits per symbol has simply gone up by a factor of two and the spectral efficiency doubles up compared to the on off keying system. So any 4 state, spectral efficiency would then simply double up, the spectral efficiency. If you go to 8 BPSK, so if you go to BPSK, the corresponding phase states that you have will be, so you have 1 phase state here, then you have 45 degree, then you have 90, 135 here, here, you know and these are the 8 possible states.

So these 8 possible states can then represent groups of 3 bits, so you have 000, 001,010,011,100,101,110,111, in this case I have not used the gray coding but I have used what is called as straight binary coding, so the spectral efficiency triples. In practice it will not exactly triple, because of the imperfections involved, so it would be slightly less than 3, but theoretically at least, you're using the same bandwidth, transmitting more than or equal to 3 bits per symbol. Therefore the spectral efficiency shoots up.

(Refer Slide Time: 26:40)




You can then go to even exotic constellation called a s16 quam, this time you have many, many implementation choices, so you can pick one of these, here you take 1 in a ring of BPSK, okay? AND then on a other ring, corresponds to increased transmit power, you pick 1 more BPSK, so if you, now look at the total 16 combinations and then binary counts, we can try this, 0000, this would be 0001, you have 0010 and then the corresponding bit here is 0011. This way you can actually fill up and we will see how to implement an modulator in order to employ this one.

O this is called as 16 quam in the configuration because you have two circles here, it is also possible to have a different kind of a quam, this is called s a square quam and in the square quam as you can clearly see they are arranged, the symbols are arranged in the form of a square. So this is one way of increasing the spectral efficiency, this is 16 square quam, you can also, both the 64 quam, but I'm not going to talk about the 64 quam in this particular module.

So you have all these options, in which you are able to transmit more bits per symbol, but what exactly is the catchier and what is the other approach in order to answer these questions, just wait for the next module. Thank you very much.

**Acknowledgement**

**Ministry of Human Resource & Development**

**Prof. Satyaki Roy**

**Co-ordinator, NPTEL IIT Kanpur**

**NPTEL Team**

**Sanjay Pal**

**Ashish Singh**

**Badal Pradhan**

**Tapobrata Das**

**Ram Chandra**

**Dilip Tripathi**

**Manoj Shrivastava**

**Padam Shukla**

**Sanjay Mishra**

**Shubham Rawat**

**Shikha Gupta**

**K. K. Mishra**

**Aradhana Singh**

**Sweta**

**Ashutosh Gairola**

**Dilip Katiyar**

**Sharwan**

**Hari Ram**

**Bhadra Rao**

**Puneet Kumar Bajpai**

**Lalty Dutta**

**Ajay Kanaujia**

**Shivendra Kumar Tiwari**

**an IIT Kanpur Production**