CMOS RF Integrated Circuits

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Module - 09
Mixers
Lecture - 26
Mixer Non-Idealities

Hello and welcome back to CMOS RFIC circuits CMOS RF integrated circuits this is lecture 26 we were doing mixers multipliers that was our module nine and what we have been talking about we have basically developed double balanced Gilbert cell mixer

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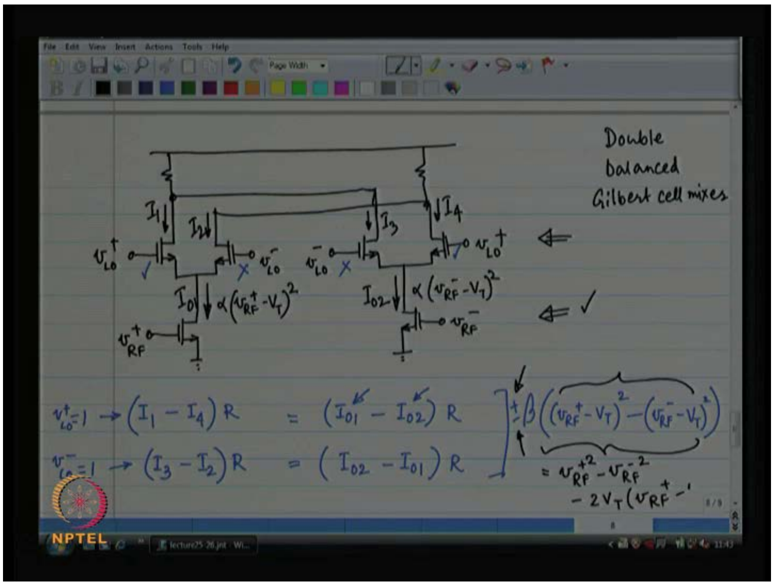

This is our double balanced gillbert cell mixer and at the end of the previous class we were struggling to figure out how we can interchange the RF and the LO terminals right this is what we were struggling to figure out at the end of the previous lecture. So, will finish with that and then we are going to talk about mixer non idealities what are the different problems with mixers how they are going to effect the radio architecture and. So, on and. So, forth all right.

So, in the last we were we ended it on the note that I can potentially move the LO to the layer of transistor on top and I can move the RF to the to the layer of transistor on the bottom . So, if I have RF on top LO at the bottom no problem whatsoever no problem at all I have some matching issues how do I match the RF signal that is coming from the

LNA to the input of the mixture input of the mixture is looking like a capacitor. So, there is not going to be any power transfer at all. So, I cannot do matching at all that is problem number 1 right.

Problem number 2 is may be the capacitance is going to be too much because there are now 4 you have to drive 2 sets of transistor alright. So, that is why we wanted to move towards bringing the RF to the bottom layer of the transistors the LO to the top layer of the transistors and this also works fine the LO is a large signal that goes on and off and I get this as my output when the LO is high I get the plus symbol over here and LO is low I get the minus symbol over here all that is fine the problem is that internally it is proportional to the square of I am sorry the difference of 2 squares of V RF plus minus V t and V RF minus minus V t.

So, if this relationship did not have the square term if it had only a linear term then I would be happy right or rather you could also represented as a plus B times a minus B a square minus B square is a plus B times a minus B right. Now, this is if V RF plus is equal to minus V RF minus. So, if you can make sure that these 2 cancel out with each other then this is, but if you cannot make sure of that if there is a common mode signal over there then V R in trouble ok.

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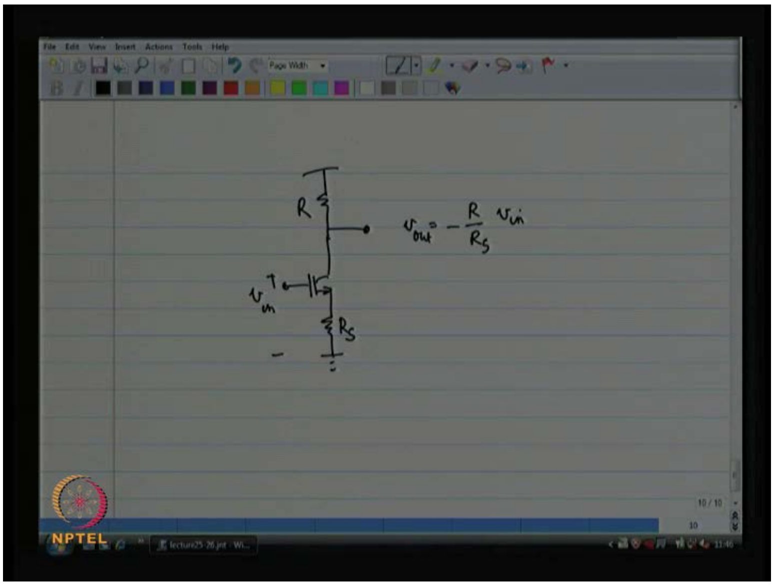

So, in general it is going to be non-linear. So, we need to linearize this and how do you linearize. So, think about this you apply V N over here small signal and the output you get if V N is a small signal then the output is minus G m R parallel R d S times V N now this works only if it is a small signal if V N is a large signal then G m itself is going to vary which is which could be our case right and then we are in trouble how do you linearize such a circuit how would you linearize such a circuit you make you introduce source degeneration right.

You put a load over here and as soon as you do that V G S you can think of V G S as a small quantity and the gain is no longer going to be controlled by G m the gain is going to be something like R by R S almost equal to this this will work as long as R S is very large R d S very large G m is large you can easily conceive of this and here this is irrespective of whether the input signal is a larger signal or a small signal right this is the way we linearize.

Now, you could also conceive of putting an inductor over there instead of a resistor even that is going to help you in terms of linearization. So, at d c is going to be nothing, but at the high frequency that will present an impedance and at that high frequency this is going to behave like a perfectly linear amplifier right. So, this is the technique we are going to use. So, this is the technique we are going to use and we can do this we can. In fact, go a step further and join these 2 grounds and make it differential that is going to reject the common mode [laugh] signal right.

What else is that going to do that will also give you a resistance looking into the gate of the mixture you remember our LNA discussion when I put when I degenerate the source with an inductor the input impedance of the LNA becomes resistive and that is great because now I can do my matching right. So, this is often done and 2 first order you need not do it because all you have to make sure is that the common mode of the RF signal is 0. So, if you do that you are all set or the common mode of the RF is a constant you do that you are all set you do not have to do anything else.

But for if you want to linearizes it get rid of the common mode signal this is 1 way of doing it the additional advantage that this gives you is that it helps you in terms of matching now you get a resistive input input as suppose to a pure capacitance alright. So, this as far as our mixture discussion goes this is how we design mixtures we make a double balanced mixture you are going to for input matching purposes you may or may not want to put that inductor over there and you are done the output of the LNA might not be might not be differential. In fact, we did not design a differential LNA at all if you look up the books thermoslese book rasavi book there are examples of differential output for the LNAS. So, you might want to check up what is in the books you also might want to check up the few papers there are lot of low noise amplifiers which have a differential output.

Typically the input of the low noise amplifier is definitely going to be single handed because there is only 1 antenna there are some fussy designer out there who have not been able to make a single handed input for the low noise amplifier they have made a differential low noise amplifier they have had to have a balloon a transformer center tap transformer kind of structure at the output of the antenna to convert the single handed antenna to a differential balanced signal to the input of the LNA of course, the noise figure of the baloo balloon if its if it has any attenuation it is going to hit you directly because you are putting it in from of the LNA right.

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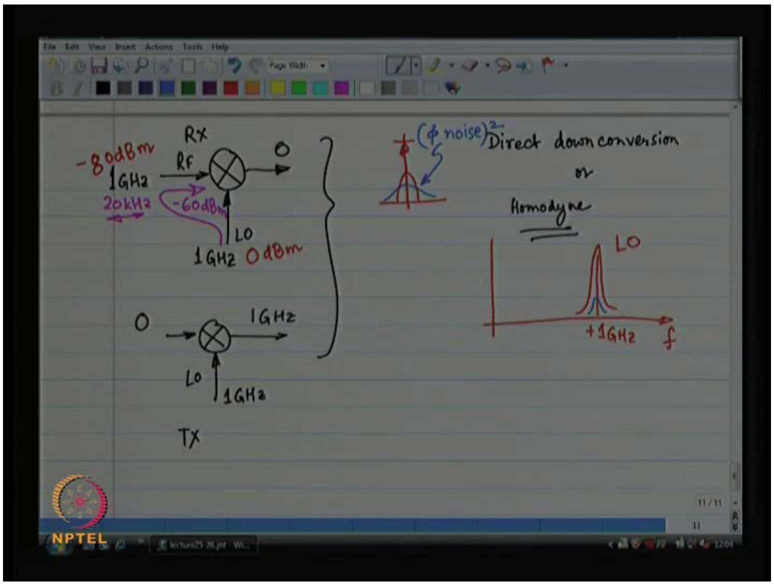

So, it is it could be a fairly common strategy to have a single handed input single handed output of the LNA which means that you have put signal only to V RF plus and V RF minus is hanging around at 0 volts or at the common mode voltage which means that you are unable to pay attention to the common mode signal of V RF plus V RF minus which means that it will be necessary for you to do linearization which means that you might want to put some inductors over there for source degeneration and linearization at the same time airtight.

Now, what are the nod idealities of this mixture the first important thing to understand is isolation between the 2 inputs of the mixtures. So, what you see over here is that 2 inputs of the mixer are really gates of 2 different mosfets. So, V RF plus there could be a parasitic capacitance between these 2 nodes there could also be a parasitic capacitance between these 2 nodes they are there c G d and c G S are there they exist there is no denying the fact which means that a potion of V RF could potentially enter through the LO terminal or a portion of the LO could potentially entered through the RF terminal right it is conceivable that this happens.

Now, does it create any problems as far as we are concern if a portion of I am going to call this I F intermediate frequency for a general heterodyne receiver this is the intermediate frequency right let us call it I f. So, let us first try to understand this lets say let us take an example let us say that the RF is at 1 gigahertz and the LO is also at 1 gigahertz which means I really want d c at the output this is this kind of a mixer would be part of a direct down conversion receiver.

So, 1 step single shot direct down conversion receiver also called a homodyne receiver all right you could also think of the scenario where as far as the transmitter is concern this is on the R x path as far as the transmit path is concern you could think of a basement signal you could modulated directly with the LO signal and you could get 1 gigahertz at the output this is direct up conversion transmitter homodyne that is the word all right.

So, let us think of both of these suppose the local oscillator leaks into the RF signal what is going to happen what is going to happen you are going to get an extra component at d c. So, you are going to get LO times the LO at d c all right think of it this way suppose the signal you are receiving from the antenna signal you are receiving from the antenna is something at 1 gigahertz with a twenty kilo hertz bandwidth this is the bandwidth around 1 gigahertz and the signal level is minus 1 hundred d V m what is d V m d V m is decibels with respect to 1 mili watt of power.

So, that is the power level that you have received at the input of your antenna now from the input of the antenna of course, there is the LNA gain etcetera etcetera lets say the

LNA has a gain of twenty d v. So, you have got minus eighty d V m at a mixer input. Now, at the LO terminal you are generating something which is a perfect tone at 1 gigahertz, but has a power level of 0 d V m and let us say that because of the leakage this is not a direct path this is a leakage path right.

There is some capacitive division etcetera and because of that when part of the local oscillator leaks into the RF terminal it gets a tain waited by sixty d v. So, the signal that leaks in is at minus sixty d V m all right. So, in that case what are you going to get at the output of the mixer well you are going to get your signal at d c and on top of it you are going to get a LO times the LO which is twenty d V larger than the signal power and that is also going to be a d c.

Is this a problem does not look like it is a major problem it is only at d c. Now, consider the fact that your local oscillator is not a perfect oscillator the local oscillator which is at 1 gigahertz you think it has a a frequency response that looks like this right you have impulse function at plus and minus 1 gigahertz unfortunately this is impossible to build if it is a square wave impulse functions at plus 1 minus 1 gigahertz then at plus 3 minus 3 gigahertz etcetera lets ignore the plus 3 minus 3 irrelevant also I am going to knock off this negative portion it is not really necessary as far as our understanding is concern.

This LO signal is impossible to generate why you are always going to generate something which has noise all right it is never going to be a perfect local oscillator it will be an oscillator and there is going to be noise along with it now this noise remember we have cut out the amplitude noise this noise is called the phase noise because that is all we have got over here. So, where the 0 crossing is right that determines the phase noise it is not at the perfect place. So, little bit off from the perfect 0 crossing.

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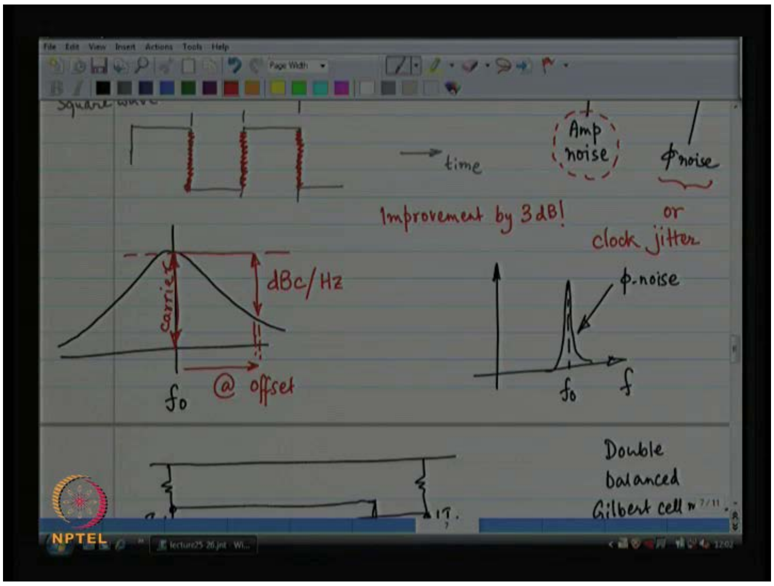

So, phase noise as far as digital designer are concerned they called it jitter clock jitter right. So, where the 0 crossing there is little bit of miss alignment over there and that miss alignment is random it varies from cycle to cycle. So, that is call fluctuater it is a same thing phase is the same as clock jitter it can do the mathematics and work it out what is exact relationship between phase noise and clock jitter how much phase noise will give you how many pico seconds of clock jitter etcetera etcetera fine.

So, there exist clock jitter which means that the spectrum of the signal when you look at the spectrum of the signal it is never going to be the perfect impulse at your desired frequency it is going to be something like that looks like an impulse, but never is going to be an impulse it is going to be something which has chords around your center frequency all rights these chords are because of phase noise and phase noise is mathematically expressed in terms of how much this chord is with respect to the scent of frequency at a given off set.

So, suppose I exaggerated and this is how the spectrum looks like and phase noise is expressed as. So, many d V S with respect to the carrier signal this is the carrier signal. So, many d V S with respect to the carrier signal d V c per hertz at and off set frequency from the scent of frequency. So, at a 1 mega hertz offset I have got eighty d V c per hertz less than the carrier minus eighty d V c per hertz that is my phase noise this is just an example.

So, now, let us go back to our example. So, your local oscillator is never going to be this perfect signal your local oscillator really is going to look like this and when you do LO times LO what is going to happen when you do multiplication in the in the time domain you do convolution in the frequency domain right when you convolve this with this this is the attain waited version of the LO what do you expect to get we expect to get the square of the LO which is spread around all right and that is going to come on top of yours signal. So, your phase noise is going to get squared by itself because of the mix and its going to spread all over your signal . So, this can prove to be a disaster as far as your design is concern. So, what do you have to do about your design if you want to design a mix for direct down conversion applications what do you have to do you have to make sure that LO leakage is minimum

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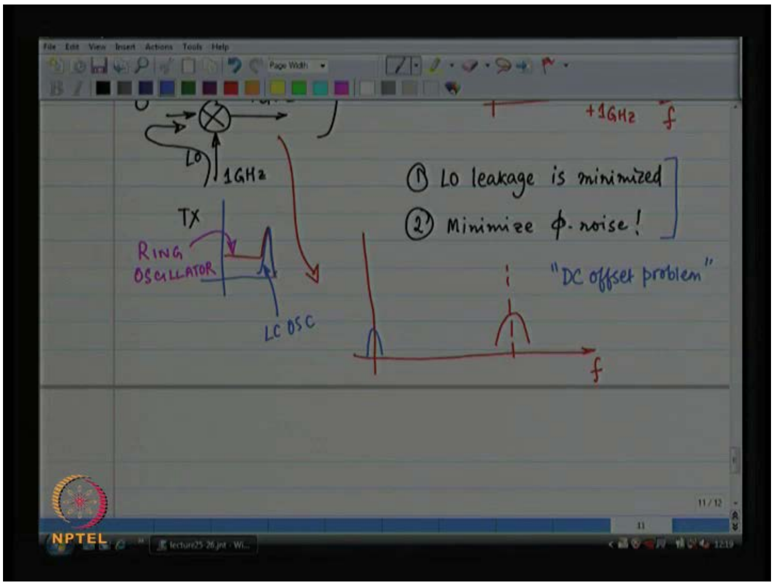

So, there should be no coupling whatsoever between the LO terminal and the RF terminal. So, there should be somehow isolated I do not know how you have to make sure of that place them far apart do all kinds of things make sure that c G d is not there etcetera all right. What else do you have to do you have to make sure that phase noise of your local oscillator is minimum right that also has to be taken care off you have to make sure that phase noise is absolutely absolutely absolutely clean there is no phase noise. So, all of these will come from the specifications.

So, if the specification is as I said then you have to make sure that even after the mixing of the phase noises the amount that you get is less than the power that you have got from your signal you need signal to noise ratio power is coming from your signal phase noise is mixing with itself that is creating some noise. So, that signal to that noise ratio has to be very very large right this is what you have to do as far as your mixer design is concern as far as your oscillator design is concern you have to make sure that the oscillator has superb phase noise properties right. Can we proceed all right.

The next non ideality is when the RF leaks into the LO is this a big problem is this a big problem at all no it is not a big problem at all because the LO is a 1 0 signal remember the LO is a 1 0 signal. So, when the switch is off it is off when the switch is on it is on right its either completely on or completely off that is why square wave helped us. So, over here either I get plus beta times something or I get minus beta times something in do not get any intermediate values over here ok.

The only time when the RF can actually leak into the LO and create a difference is at the transition edge at that edge if RF happens to mix into the leak into the LO then I get some problems then RF mixes with RF and creates double the signal square of RF square of RF is definitely oh first of all RF is going to mix with RF with attenuation the square of RF with attenuation is going to be much less than RF mixed with L o.

So, you will get something down here compare to the RF itself. So, this is not that serious problem as far as we are concern right it is not that serious as far as we are concern is the LO leaking into the RF path the LO is a large signal it can leak easily get into the RF path the RF is a small signal when it leaks into the LO path in becomes even smaller the LO is gigantic compare to the R f. So, it is not really something which is very serious.

So, we are not going to worry about it. What is worry some for us is the local oscillator leaking into the RF path. What about in the transmit case same story local oscillator leaking into the d c when the local oscillator leaks into the d c I get the square of the local oscillator with some attenuation now remember that the local oscillator is not a perfect signal there is a phase noise associated with it and when there is phase noise associated with it I will get the square of the phase noise on top of the d c is this a problem what does the output spectrum look like at 1 gigahertz I have my signal and the LO times the leaked LO is at d c.

So, it is not going to cloud my signal at all . So, this is not a terrible issue as far as we are concerned if the LO signal looks like this if the LO signals looks like this this is not a terrible problem. If the LO signal happens to look like this then this is still going to be a problem right there are times when the LO signal does look look like this this red curve with some d c and that is when you make a ring oscillator if you make an L c tank inductor capacitor tank and you make an oscillator out of the inductor capacitor tank then typically this is not going to be the case your L c oscillator will have a characteristic like this in which case you are saved from this problem.

However if you made a ring oscillator then the LO will have significant component at d c there is going to be noise at d c phase noise at d c which means that that is going to become a significant problem as far as your transmit is concern ok. We will look at oscillators and this phase noise business and where it is coming from and will we will take a look at all of this, but this is just a prelude take it as a prelude to what is coming in future ok.

So, we kind of understand the direct down conversion problem LO can leak any time into the RF signal and as soon as that happens you get a d c off set you also get phase noise problems this seems like a something which is un avoidable both of these problems are. So, hard to solve that its almost intractable right and this is 1 of the reasons these 2 problems are 1 of the main reasons why direct down conversion is discounted as a popular method popular radio architecture.

These two negatives as far as direct down conversion are concern are. So, big that direct down conversion is discarded and in many cases thrown up they are not options at all. So, typically what happens is that when your signal bandwidth is small your signal bandwidth is. So, small that phase noise can easily cloud the signal bandwidth phase noise square can easily cloud the signal in those case direct down conversion is almost not possible as an architecture as a vibal architecture we have to go for something else right.

In cases where the signal bandwidth is significantly large typically these are c d m a kind of signals c d m a code division multiple access right w c d m a wide band code division multiple access wi max that is time division multiple access, but it has a wide bandwidth they do a lot of spread spectrum techniques frequency hopping is there then O F d m right O F d m techniques are also used in wi max the next a 2 2 dot eleven your standard wi fi there also the bandwidth is large you are using O F d m your bandwidth is fairly large and when the bandwidth is fairly large then the square of the phase noise is only a small portion of the total signal which means that the signal is never going to be clouded by the square of the phase noise because your signal is much broader right.

So, this is the basic idea that if my signal has a wide band then the square of the phase noise is not going to cloud me I can use direct down conversion direct down conversion is a very simple architecture you have the RF you mix with a signal which is with an LO signal which is tune to the RF signal and you directly go to base band and then at base band you put a low pass filter and then after the low pass filter you put you're a to d converter and you figure out what has been transmitted right this is very popular architecture when the signal bandwidth is large. So, system like wimax w c d m a c d m a and a 2 2 dot eleven typically typical receivers in these archi in these standards will be direct down conversion.

However when you go for narrow band communication protocols for example, G S m G S m is most widely used cell phone standard or older stuff like amplitude modulation frequency modulation t d m a standards older standards of t d m a etcetera if you talk about any of these architectures direct down conversion is almost never used because of this intractable problem of LO leakage phase noise of the local oscillator and. So, on all of these cause problems because of the no bandwidth of the signal there is this is traditionally called the d c offset problem it is not necessarily at d c that it happens, but it is called the d c offset problems.

So, because of the d c offset problem d c is a large portion of the narrow band signal right d c and surrounding frequencies are everything that you have so that is why it is called the d c offset problem and because of this problem direct down conversion is almost never used in standards like G S m then what is used. So, the most general radio architecture is something which is called super hetero heterodyne, but before we go to super heterodyne let me talk about heterodyne.

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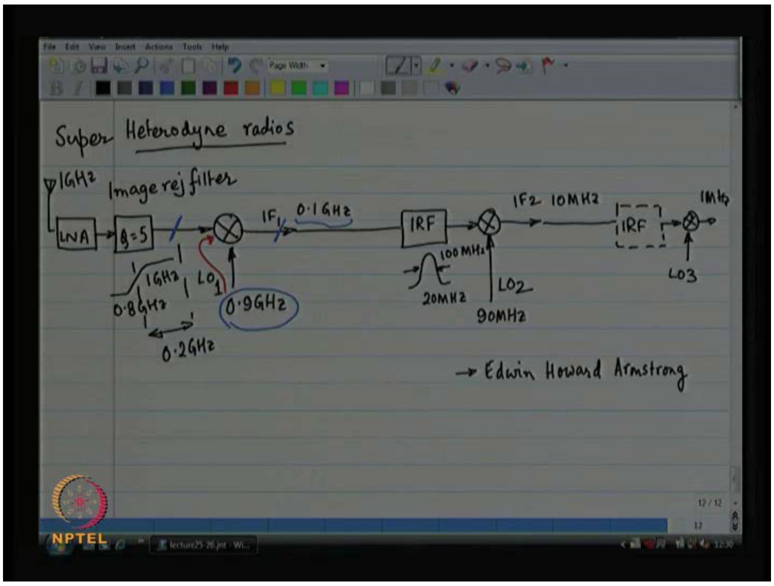

So, let us do it by example let us say that my RF signal at 1 gigahertz now I am going to choose the LO signal at say a frequency of point nine gigahertz when I mix when I multiply a 1 gigahertz signal with a point nine gigahertz signal I expect 2 outputs 2 output frequencies I expect something coming out at 1 point nine gigahertz something else is coming out at point 1 gigahertz ok. Of course I am going to low pass filter this and I am going to take the something which is produce at point 1 gigahertz right this point 1 gigahertz is the intermediate frequency also called the I F.

So, this is I haven't finished yet this is almost what super heterodyne stage looks like. So, you have got the low noise amplifier there is something in between we haven't yet come to that and that is coming from the antenna from the antenna you go to the low noise amplifier from the low noise amplifier you go to the mixer the mixer mixes with a local oscillator which is not exactly the RF signal, but close and as a result it produces an intermediate frequency.

Now, think of LO leakage if the local oscillator leaks through is there any problem no problem because when it leaks through it produces a d c d c and neighboring stuff, but I am not interested in d c my signal goes to point 1 gigahertz right. So, I can easily cut off the stuff that is at d c it is very easy to cutoff d c and neighboring stuff all right.

The problem here is that not only with 1 gigahertz go to point 1 gigahertz if there is a blocker at point eight gigahertz what is going to happen to that the blocker at point eight gigahertz will also go to point 1 gigahertz right if my if there is there exist a signal which the antenna picks up a large signal may be your friend is talking to his friend at point eight gigahertz right that signal will also couple in and it will fall exactly at point 1 gigahertz now this is a problem because the blocker is falling on top of your signal cannot let that happen.

So, what we put over here is something which is called an image reject filter the job of the image reject filter is to keep your desired signal and to get rid of the blocker if your local oscillator is at point nine gigahertz if your signal is at 1 gigahertz then the image reject filter should be a filter that cuts out point eight gigahertz allows point allows 1 gigahertz through something like this all right.

Now, how difficult is such a filter to build its impossible to make a brick wall filter no surprise right the image reject filter is some sort of a band pass filter looks like a some sort of a band pass filter and q the quality factor of this band pass filter is the ratio of the center frequency to the bandwidth if I want the bandwidth to be small then I need a large q large q is very difficult to build.

So, the lowest bandwidth that I the largest bandwidth that I can allow is something which is around let us say 1 hundred megahertz mid between 1 gigahertz and point eight gigahertz separation midpoint of that is point nine gigahertz which has a separation of hundred megahertz so; that means, that I can allow for a bandwidth of 200 megahertz which means that the q of this band pass filter is about 5 which is not very difficult to build all right.

So, what does this tell you this tells me that this local oscillator over here cannot be very very close to the RF signal it needs to be a little bit away from the RF signal if the RF signal is at 1 gigahertz LO can be at point nine gigahertz that will give me a q of five for the image reject filter, but if I want my LO to be at point nine nine gigahertz then a need a q of 50 which is very very hard to build as far as the image reject filter is concerned.

So, the intermediate frequency will be a significant fraction of the original frequency. So, here the intermediate frequency I have chosen in point 1 gigahertz if I wanted point 0 1 gigahertz then LO would be point nine nine gigahertz then my q would be this frequency divided by the I F frequency by 2 or. So, so that will be the q of the image image reject filter that you need. So, large qs are very difficult to get. So, you make something with a small q right which means that you need your I F to be a significant fraction may be 1 tenth of your RF now that is probably no good because if I want to put my a to d converter if I want to put my low pass filter then this is no good I mean I cannot do a to d conversion at hundred megahertz it is very hard right I would rather do it a ten kilo hertz or hundred kilo hertz not at hundred megahertz.

So, you put another stage. So, you put another image reject filter you put another mixer and you put another LO S let us say now you choose your LO to be ninety megahertz image reject filter to cut out eighty megahertz and allow hundred megahertz ok. So, you have got your I F now your I F second intermediate frequency is at ten megahertz. So, you have got a second stage then you can go for a third stage and. So, on and. So, forth then you have got 1 megahertz right.

So, this in general is the super heterodyne radio this entire scheme of things you put you make 1 heterodyne stage you used the heterodyne stage as a building block step by step by step you go down in terms of frequency every time you generate 1 local oscillator you have a mixer and you have an image reject filter right you need 3 local oscillators here running at 3 different frequencies it can be done trust me it can be done ok.

You have 3 different oscillators at 3 different frequencies you can make all of these frequencies and make this it will work there is no problem this is the most general radio architecture radio receiver architecture as I have shown over here all right it is called the super heterodyne radio and person attributed for this work his name is edwin howard armstrong. So, I should mention a brief give you a brief very brief history about this gentleman edwin howard armstrong.

He is the last of the solo inventors what is solo inventors solo inventor is you know the era of edison and faraday and tesle 1 man inventing something we do not have that anymore nowadays company build something we no longer invent anything to start with they build some product or team of engineers develop a certain product I phone and I pad and just the cell phone itself or anything that you are talking about the computer it is made by a team of engineers.

So, this invention word has gone. So, edwin howard armstrong was the last of these solo inventors and he was a engineering student electrical engineering as a student he developed those were the early days of the radio at that time people did not know what is going on and there was complete lack of understanding of entire subject maxwell's laws were not even there right.

So, at that time he invented the regenerative amplifier. So, he made an amplifier with vacuum tube etcetera and this used the concept of positive feedback and would could amplify a very small signal into a very large signal. So, this he did as an undergraduate student and then as a graduate student he developed the super heterodyne radio architecture this this what that I showed you today was developed by this gentleman as a graduate student and then he became a professor and he invented F m radio the entire bases of F m radio right.

From the mathematics to building the transmitters building the receivers as well as white scaled distribution of these transmitters and receivers right all of this was done by him and at that time he was a professor. So, undergraduate then graduate and then professor this work was done as a graduate student. So, that is here super heterodyne receiver we are going to stop this as a we are going to pause and we are going to carry over from next class with this note we have now developed some understanding of radio architectures how the mixer fits in where it fits in and why radio architectures kind of revolve around the mixer with this note we are going to stop and we are going to carry forward in the next class.

Thank you.