WEBVTT

1
00:00:20.130 --> 00:00:22.050
We'll get started with a webinar.

2
00:00:23.700 --> 00:00:24.990
Good morning everyone.

3
00:00:26.280 --> 00:00:29.910
Blair Fuller: Thank you for joining our distinguished lecture today.

4
00:00:31.290 --> 00:00:48.210
Blair Fuller: I'm going deep saying, I'm the division director for the computer and network Systems Division and the size Directorate at at NSF. So on behalf of NSF and sighs It's my pleasure to welcome you to our Distinguished Lecture.

5
00:00:49.950 --> 00:00:54.870
Before we get started, just wanted to let you know that if you have during the webinar.

6
00:00:57.000 --> 00:01:10.590
If you have any questions, please use the Q AMP a feature to type in your questions and I will relay those questions. Typically we hold off on the questions until, until the webinar presentation is over.

7
00:01:11.580 --> 00:01:24.750
Also want to remind everyone that they will be officers health from 3pm to 4pm today for further engagement with our distinguished speaker today's so I would encourage you to join.

8
00:01:26.130 --> 00:01:46.050
The office hours as well. So with that, I'd like to introduce our speaker today is our speaker today is Dr. Thomas data and Dr. Thomas Masada is the distinguished industry professor at NYU tendon School of Engineering and also the director of NYU.

9
00:01:47.580 --> 00:01:59.640
So he received this electrical engineering and PhD in electrical engineering from MIT in 1978 and his MS in systems engineering from Japan and 1973

10
00:02:00.510 --> 00:02:15.030
So prior to joining and why you in 20 2017 he had helped pre industrial careers before at Schlumberger in another one at MIT Nicole's Research Corporation and then at Bell Labs.

11
00:02:16.470 --> 00:02:23.760
So one of the notable items. Was that at the at Bell Labs. He directed the communication and statistical sciences department.

12
00:02:26.340 --> 00:02:36.780
And we're and he was elected the Bell Labs fellow, and that's when he originated the massive my Mo, which is one of our coordinators students for the fifth generation wireless technology.

13
00:02:37.440 --> 00:02:51.120
So he's the elected member of National Academy of Engineering and also a fellow fellow IEEE. There are numerous other distinctions that he has, which you can I would invite you to read his full bio for that.

14
00:02:52.350 --> 00:03:03.840
So with that, it's my pleasure. Again, to welcome Dr Mirza to give our distinguished lecture today we'll be talking about wireless power crosses principles and prospectus.

15
00:03:05.220 --> 00:03:16.380
Tom, please take it away. Okay, thank you. Good. You like really to thank NSF size for inviting me to this seminar. It's a great honor.

16
00:03:17.400 --> 00:03:30.480
So I will talk about wireless power transfer today and we're going to be really ambitious here and talk about how could one possibly deliver wireless powers.

17
00:03:31.230 --> 00:03:45.870
That range of 100 meters or so before we get into technical things. Let me just talk a little bit about why you wireless so NYU wireless happens to be the largest Research Center in Canada and School of Engineering

18
00:03:46.350 --> 00:03:52.560
It was started by Ted Rappaport who is the person here. Ted found in two other

19
00:03:55.140 --> 00:04:04.680
Academic wireless centers which are still thriving one in Virginia Tech. The other University of Texas at Austin. He's been at

20
00:04:05.310 --> 00:04:25.860
NYU for about eight years. I took over directorship of NY you were two years ago. So we have a couple of dozen faculty 60 students and we have 15 industrial affiliates the industrial affiliate members. I'll show you the list like a minute or two.

21
00:04:26.970 --> 00:04:46.080
Interact with us, they they fund our research is no strings attached research funding for best storage. This enables our professors to have some money to do really risky research. And so our mission pretty clear what it to be students, our number one priority.

22
00:04:47.400 --> 00:05:07.170

We want to lead the way and future generations of wireless and we want to be of use to industry. And here our industrial affiliates enable us to keep on top of industrial needs and also we have this gives a mechanism for us to transfer research results to industry quickly.

23
00:05:08.700 --> 00:05:22.260
So we are professors handle all sorts of aspects. I'm one of the more theoretical types we have elza air kip and information theorist at the other end, we have

24
00:05:22.800 --> 00:05:36.660
People looking at the upper layers scheduling and so on for the wireless stack one of our Associate Directors is with our medical school, the NYU medical school and

25
00:05:37.890 --> 00:05:47.970
Has an MD and works on some fascinating problems. So we really are well poised to tackle all aspects of wireless

26
00:05:50.010 --> 00:05:57.630
Our efforts are divided among six different research thrusts my own is in foundations.

27
00:05:58.650 --> 00:06:08.040
But Ted Rappaport naturally is moving on to ever higher frequencies. He and his students and Professor rangan are

28
00:06:09.030 --> 00:06:29.520
Conducting propagation experiments both indoors and outdoors outdoors up above 200 gigahertz. These days we have people working on quantum devices and circuits interesting applications. How, for instance, to control drones with five g with the 5G network, for example.

29
00:06:31.440 --> 00:06:37.620
With people working in test beds and prototypes and so it's it's quite a lot.

30
00:06:39.150 --> 00:06:53.610
We have here our affiliates NSF is sort of at the center, not exactly an affiliate, but in many respects of an affiliate and these represent some of the leading wireless companies in the world. So

31
00:06:55.260 --> 00:07:00.090
So I was asked to say something, a few personal things about myself. So, so I was

32
00:07:01.200 --> 00:07:07.050
I'm an East Coast person was born in 1951 in Washington, DC.

33
00:07:08.130 --> 00:07:18.240
My father was a electrical engineer. He worked at National Bureau of Standards, which was renamed itself. Some years ago, NIST

34
00:07:19.890 --> 00:07:30.990
First in his family going back as far as one wishes to to get a college education. He did it the hard way between 1956 and

35
00:07:33.060 --> 00:07:45.360
He attended, University of Maryland half time to get his bachelor's degree in electrical engineering while working full time National Bureau of Standards and raising a family five children.

36
00:07:47.130 --> 00:07:58.170
Early on I learned how to solder. I remember my father helping me build a crystal radio and I was a boy and those days we lived a

37
00:07:58.590 --> 00:08:13.860
Mile from University of Maryland and line of sight to the WRC AM radio station tower. So with a loud speaker and a matching transformer my crystal radio could easily be heard across the room.

38
00:08:15.900 --> 00:08:30.960
I attended. And yes, a number of schools. What I'm singling out here is my high school Gonzaga college High School in Washington. This is it. North Capitol Street and I Street just about seven, eight blocks north of the capital.

39
00:08:31.860 --> 00:08:46.800
One of the oldest schools in Washington celebrating its 200th anniversary this year. And why am I talking about it because it was by far and away the most competitive school that I ever attended so after the first year.

40
00:08:48.060 --> 00:08:51.660
They grip students, according to

41
00:08:53.550 --> 00:09:04.350
Perceived abilities and I wanted to go into the science and mathematics section. Initially, I didn't get in but my father phone the headmaster and said,

42
00:09:04.800 --> 00:09:14.010
Either that boy goes into that group or I'm pulling them out of the school. So that's how I got into this elite group. So we started as 25 students

43
00:09:15.060 --> 00:09:27.750
Took all classes together for three years. By the end of the third year there were fewer than a dozen of us left. And in that group of students. I never ranked more than about six

44
00:09:28.950 --> 00:09:39.840
The students were that good and it was that competitive. So when I went to MIT, starting in 1968 I thought MIT was easy and comparison.

45
00:09:40.650 --> 00:09:50.340
So at MIT I initially started out as a chemistry major, and then switched to physics and my second year.

46
00:09:50.700 --> 00:10:00.360
And finally, electrical engineering and my third year the electrical engineering subjects in those days were very well taught at MIT.

47
00:10:01.020 --> 00:10:19.410
Though there were no labs attached to the regular core classes. So actually I in comparison to the way earlier engineers were educated. I had probably not as much lab experience as would have been desirable.

48
00:10:20.220 --> 00:10:34.470
But that's the way education goes so I had three careers in industry, before going to NYU, four years ago. So Schlumberger goal research was a

49
00:10:35.850 --> 00:10:37.680
Deals with they still exists.

50
00:10:39.960 --> 00:10:47.460
This is in the field of petroleum exploration at the time they were building up their research lab in Connecticut.

51
00:10:48.960 --> 00:11:01.890
And over a period of five years hired 100 PhDs and also single handedly pushed up starting salaries for engineers physicists, chemists mathematicians computer scientists

52
00:11:03.240 --> 00:11:11.670
Was with very good people here. For example, I went in there, not knowing how little I knew. So I thought that

53
00:11:12.360 --> 00:11:22.320
Knowing or having done a PhD and statistical signal processing that I knew something about 48 transforms. Well, I found it embarrassing a bit

54
00:11:22.710 --> 00:11:31.410
To see that wave propagation people elastic wave propagation electromagnetic wave propagation really knew the complex playing much better than I did.

55
00:11:32.130 --> 00:11:43.620
I spent eight years in the defense industry of this was applying traditional statistical pattern recognition techniques to for example motion detection and video

56
00:11:44.820 --> 00:11:51.390
Discrimination algorithms for ballistic missile defense radar interpretation and so on.

57
00:11:53.520 --> 00:12:04.440
1995 until I went to Bell Labs in 1995 I had never worked in communications at all. I had studied in grad school, but

58
00:12:05.010 --> 00:12:17.730
For nearly 20 years hadn't opened up a book on the subject and I got to Bell Bell Labs by well circuitous route. My wife is a PhD, computer scientists Ingrid carbon

59
00:12:18.180 --> 00:12:37.980
She was recruited by Bell Labs in 1995 to come and head a research department and I came along and was offered a one year term position, which lasted for 23 years. So I was fortunate throughout my career to work with people smarter than myself.

60
00:12:39.270 --> 00:12:43.800
Quite often, almost always knowing a lot of things that I didn't know

61
00:12:45.330 --> 00:12:56.550
And the other aspect is that this is a bit unconventional because these three areas petroleum defense and telecommunications are quite different and so

62
00:12:57.750 --> 00:13:11.010
That actually worked for me because I've always been able to pull things from one field and use them in another field. So I think I will now go on to the topic at hand, namely wireless power transfer

63
00:13:12.570 --> 00:13:30.630
So everybody's familiar of the wireless power is a fact. Now, but it extremely short ranges. So electric toothbrush chargers, for example, our wireless their inductive. And why would that be so it's pretty easy to figure out. I mean, if you had electrical contacts.

64
00:13:31.980 --> 00:13:38.550
Imagine what happens when dried up toothpaste gets on them. They're not going to work very well. And besides, good quality.

65
00:13:39.630 --> 00:13:50.400
brass, nickel plated brass of contacts are expensive, so it's probably cheaper to go wireless. But what we're interested here is really what, what can we do

66
00:13:50.880 --> 00:14:00.570
on a much bigger scale. And now you can't do this. Nobody's seen a drone flying around operated by wireless power.

67
00:14:00.990 --> 00:14:09.420
operating rooms and hospitals there cables all over the places and factories, one could imagine what, what if you could

68
00:14:10.050 --> 00:14:21.690
The robots in a factory. What if they could be completely untethered and didn't have to constantly go back and recharge their batteries so we don't know how to do this yet, but that's why this is an interesting problem.

69
00:14:22.140 --> 00:14:28.380
The good thing is there are no known physical principles standing in the way we just have to

70
00:14:29.580 --> 00:14:32.940
Really put the shoulder to the wheel and do some very

71
00:14:34.410 --> 00:14:39.690
Inventive research. So one first thought with wireless power transfer

72
00:14:40.140 --> 00:14:51.420
Is being farming and a couple of ways to do this. I could have a dish antenna that focuses power and mechanically steer it or I could have electronically sterile phased array.

73
00:14:51.720 --> 00:15:03.420
I don't think this is the answer. And let's just do some back of the envelope calculations. So let's suppose my transmitter puts out some power and what's now.

74
00:15:04.320 --> 00:15:16.950
The transmitter antenna has some game G sub t focuses the power and over certain angles we divide by the area of a sphere of radius are

75
00:15:17.490 --> 00:15:27.900
This gives us the power density and units of watts per meter. There's a standard formula for relating the gain of an antenna to its

76
00:15:28.740 --> 00:15:47.340
To its effective area radiating area at we do that here. So we have watts per meter. We not multiply watts per meter times the effective area of our receive antenna at our drone. This is the receive power, and so our

77
00:15:47.850 --> 00:16:02.040
We have a very simple formula for the non dimensional power transfer efficiency and if we want this efficiency to be in the neighborhood of one, that means, guess what the geometric mean of the

78
00:16:03.240 --> 00:16:18.150
Effective areas of my transmit receive antennas has to equal the product of the wavelength and the range of which we want to operate. Let's suppose our drone is 100 meter range. Let's suppose the drone has a

79
00:16:19.410 --> 00:16:24.690

receive antenna 10 centimeters on a side so

80
00:16:26.370 --> 00:16:40.110
Okay, so it's not a big drone and we plug into this formula. And what we're going to do is for three different carrier frequencies we have the associated wavelengths. And then we have the aperture.

81
00:16:40.830 --> 00:16:54.840
A sub t the transmit aperture in meters needed to do the job. So if we started three gigahertz. This is 10 centimeter wavelength. Our transmit antenna has to be, guess what.

82
00:16:55.290 --> 00:17:10.320
100 meters across, which is comparable to the range of which we want to operate. That seems a bit ridiculous. So we jump up a factor of 10 to 30 gigahertz. And now we are one centimeter wavelength. Okay.

83
00:17:11.280 --> 00:17:21.330
Still pretty big aperture 10 meters on a side. And finally, we go to 300 gigahertz millimeter wave. Ah, the aperture is one meter on the side.

84
00:17:21.720 --> 00:17:25.680
This, actually, this looks rather favorable. But now, think of it.

85
00:17:26.370 --> 00:17:39.300
In all cases, our square antenna is 1000 wavelengths on the side. So if we wanted to this to be a phased array, we would have to have. Guess what 4 million

86
00:17:39.600 --> 00:17:53.160
Antennas half wavelength antennas and it's the same irrespective of the carrier frequency 4 million for this 4 million for this and 4 million for this. So it's, yeah, maybe it's possible to do something.

87
00:17:53.820 --> 00:18:07.620
With these classical been forming techniques, but it doesn't look all that promising and from a research standpoint, there's not much more than somebody like myself a communication theorist can contribute. So we're going to look elsewhere.

88
00:18:09.210 --> 00:18:16.470
So in order to understand a wireless power. We have to understand how antennas function and

89
00:18:18.270 --> 00:18:33.690
This can win what learns list and undergraduate engineering school. It looks like a very bewildering subject because what if I always talk about a hertz Ian dipole, which is infinitesimally short antenna.

90
00:18:34.560 --> 00:18:48.810
hired a hertz hundred 50 years ago of figure out exactly how this antenna functions what its radiation power is so then

what did they teach you. Well, we actually make the antenna half wavelength long

91
00:18:49.080 --> 00:18:54.360
And we make some assumptions about the current distribution. And for instance, we find that

92
00:18:55.140 --> 00:19:11.280
It's radiation impedance as well to 70 homes or something like that and and as so it's all seems very complicated. And of course, if you really want to find what the current distribution and actual antenna is it's a very involved.

93
00:19:12.090 --> 00:19:24.360
numerical calculation, essentially. And what happens with systems of antennas. How do they interact. So it isn't an all clear yet. There's a very simple picture, which is circuit theory. So

94
00:19:25.050 --> 00:19:40.320
Circuit Theory of Communication professor. You also have Gnostic have to you mention did some very fundamental work on this. Here's a couple of other at references that you all can look at, at your leisure. But

95
00:19:41.850 --> 00:19:51.990
The old fashioned network theory is something that isn't talked too much in engineering schools these days, they were already phasing it out at MIT, when I was an undergraduate.

96
00:19:52.500 --> 00:20:07.800
In the late 1960s. Interestingly enough, one of our emeritus professors Dante, you will about five years ago did a very nice book on this topic classical network theory and he's over 90 years old now and

97
00:20:08.850 --> 00:20:20.040
Notable achievement. All right. But when you talk about networks. Well, any sort of antenna a resistor a capacitor has two wires leading into it.

98
00:20:20.370 --> 00:20:28.170
And it's called a ported device because the current going into one of the wires, is equal to the current coming out of the other wire.

99
00:20:28.470 --> 00:20:42.330
And there's some voltage across these two antennas voltage is related to current by a complex impedance. Now I take antennas, or n microphones or and loudspeakers

100
00:20:42.660 --> 00:20:58.290
But I'm in close proximity and now I have an important network. And so it's characterized by n voltages and currents and a n by n square impedance matrix. So,

101
00:21:00.090 --> 00:21:07.140
This is just the relationship between the currents and the voltages and you can write it out and vector matrix form.

102
00:21:07.770 --> 00:21:23.550
for all intensive purposes, unless you really have some man made structures deliberately designed to behave in such a unusual way you have reciprocity, which basically means that

103
00:21:24.990 --> 00:21:36.840
This matrix impedance matrix is equal to its unconscious gated transpose. There aren't too many requirements on this matrix. The real part has to be non negative definite because any

104
00:21:37.350 --> 00:21:50.670
Being a pass us a system of passive devices. If I feed any current at all in anywhere into this network. There has to be some positive or non negative dissipation of power and that's what we mean here.

105
00:21:52.470 --> 00:22:10.080
So before we talk more about a network of antennas. Let's just review a an exercise we all went through and undergraduate school. So here I have a voltage source with some internal impedance Zs we want to connect this

106
00:22:11.310 --> 00:22:23.370
Imperfect voltage source with a some sort of load impedance and we want to choose the load impedance to extract as much power as possible from this voltage source.

107
00:22:24.060 --> 00:22:37.500
So the classical solution is we directly work with his load impedance we write out the load power in terms of what the square of the voltage

108
00:22:38.640 --> 00:22:48.060
The real and imaginary parts real parts are primed imaginary parts are double primed of the source impedance and load impedance and guess what the

109
00:22:48.750 --> 00:22:59.370
The optimum load and Pete and should be the complex conjugate of the internal impedance of the voltage source and this is the expression we get for the maximum possible power.

110
00:22:59.850 --> 00:23:04.470
Now we're going to have to do a similar exercise with these networks of antennas.

111
00:23:04.800 --> 00:23:19.800
But I don't want to do an optimization over an impedance matrix. Instead, I can actually do all optimizations over vectors of current. So instead of optimizing over a square matrix. I'm just going to optimize a recurrent vector

112
00:23:20.220 --> 00:23:27.300
And so we can use the same trick here. So we forgot about this impedance and what we do is we focus on the load current

113
00:23:27.570 --> 00:23:32.370
And what we're going to do is adjust to the load current so that we pull the maximum power out

114
00:23:32.670 --> 00:23:43.170
This might you might think that gosh, we're going to be cheating or letting ourselves open to cheating if we can arbitrarily set this load current to be anything we want.

115
00:23:43.560 --> 00:23:51.480
But if we actually make this load current to grade it turns out we're going to be feeding power back into the voltage source so

116
00:23:51.720 --> 00:24:08.280
Again, we forget about the impedance entirely the load impedance work only with load current and we get the same result. This is a really useful trick. I'm not saying I invented it, but like so many things. One, one didn't learn it in school and it's tough to find in the literature.

117
00:24:09.480 --> 00:24:22.080
So now let's consider the problem at hand power transfer between two arrays of antennas, or this could be acoustic problem two arrays of microphones or loud speakers.

118
00:24:22.410 --> 00:24:33.780
So here we have a transmitter. A with em antennas described by a current vector and a voltage vector. And we have a receiver, as described by a current vector

119
00:24:34.560 --> 00:24:42.780
I in a voltage vector V and the voltages are related to the currents through a partition impedance matrix.

120
00:24:43.500 --> 00:24:52.800
So what we're doing here was we what we want to do here is get rid of the voltages and simply write out the transmitted power in terms of the

121
00:24:53.040 --> 00:25:01.650
Transmit current and the receive current we want to ride out the receive power in terms of the transmit current and receive current

122
00:25:01.920 --> 00:25:09.480
So we start with course with the voltages. So the transmit power we simply take each antenna and multiply.

123
00:25:09.690 --> 00:25:18.690
The voltage appearing on that antenna by the conjugate of the current going into that antenna and we sum up over all the antennas and take the real part.

124
00:25:18.990 --> 00:25:36.510
Well, we can get this voltage from this Peters relations. So we can eliminate voltage and this is what we get. So this is our transmitted power in terms of I Am the transmitted power or current vector, and I am the received current vector

125
00:25:37.620 --> 00:25:42.150
Sorry receive power, it's just the opposite sign because of current

126
00:25:42.750 --> 00:25:52.620
By convention, current is still going into the antenna, we want to take the current coming out of the antenna. Hence, minus sign. So we have a very similar expression.

127
00:25:52.860 --> 00:26:03.180
For receive power, now we're just going to take the ratio of received power to transmit power. That's the power transfer efficiency. So here's our expression.

128
00:26:03.720 --> 00:26:12.150
And now we're going to, we're now perfectly free to choose the transmit currents. I am the receive currents I and

129
00:26:12.510 --> 00:26:21.600
It's pretty clear that if we just uniformly double everything transmit receive currents. We have exactly the same efficiency as before. Nothing changes.

130
00:26:22.140 --> 00:26:33.960
Well, two strategies come to mind. One is call it a greedy strategy, which is not really a non cooperative strategy. So whatever current

131
00:26:34.650 --> 00:26:41.250
Is being transmitted. I am the receiver essentially tries to draws

132
00:26:41.700 --> 00:26:52.080
As much power is possible OUT OF IT system of antennas doesn't care what caused this is, of course, to the transmitter antenna, it's just going after optimum power.

133
00:26:52.350 --> 00:27:01.380
So, pretty easy to get the this greedy received current in terms of transmit current and re substitute into our efficiency.

134
00:27:01.620 --> 00:27:09.900
Now we've eliminated the track of the receive current. All we have is an expression of transmit current which we can optimize over

135
00:27:10.680 --> 00:27:26.340
What happens. Well, our, our efficiency will never exceed 50% if we use this greedy strategy. It's a bit like the trying to

classical problem of pulling maximum power out of a

136
00:27:27.420 --> 00:27:36.660
Sort voltage source having an internal impedance. Now, if instead we jointly cooperatively optimize the

137
00:27:37.140 --> 00:27:42.600
transfer efficiency over both the transmit currents and the receive currents

138
00:27:42.930 --> 00:27:56.670
We have a completely different problem. And we're not restricted by this maximum 50% efficiency and all of these optimization problems. By the way, are generalized eigenvector eigenvalue problems. Let's go back to the previous

139
00:27:57.180 --> 00:28:10.290
Let's go back to this classical problem of the voltage source here what to get around how to get around this. Well, it seems to have been Thomas Edison realized. And in fact, until the time of Thomas Edison.

140
00:28:10.770 --> 00:28:18.330
It was customary to try to pull as much power as you could out of an electrical generator and the Smith, making the load.

141
00:28:19.020 --> 00:28:31.500
Resistance equal to the internal resistance of the generator with 50% efficient Edison came along to design of working on his electric

142
00:28:32.040 --> 00:28:43.140
Power distribution and lighting system and said, Why should we do this, why not make the load impedance much bigger than the internal impedance of the generator

143
00:28:43.440 --> 00:28:58.200
He did that and of course with other refinements in generators, he made generators 10 100 times bigger than they'd ever been made before with efficiencies above 80% 80 85% one reads and

144
00:28:58.980 --> 00:29:06.120
So this there's some moral lessons in this or philosophical lessons. I want to talk a little bit about this later, but

145
00:29:07.290 --> 00:29:08.580
All of this, of course,

146
00:29:09.840 --> 00:29:21.720
Was governed by owns law voltage equals current times resistance and jewels law power equals voltage times current and at the time anybody

147

00:29:22.110 --> 00:29:29.880
Any good who worked with electricity in those days, this was in late 1870s new these two laws.

148
00:29:30.600 --> 00:29:45.210
The fact is the most brilliant physicists in the world at the time didn't realize the implications of homeless law and jewels law. So we tend to think Edison's work was inventing the light bulb that was only one part of it. He himself called it

149
00:29:45.960 --> 00:29:57.330
Guess watch subdividing the electric current. In other words, generation of electrical power and distribution was almost the biggest thing that he did and

150
00:29:59.490 --> 00:30:08.880
I could talk all day on Edison, but let's. The point is knowing the mathematics behind a problem doesn't mean you really understand the problem.

151
00:30:09.540 --> 00:30:15.540
Okay, that's the philosophic lesson. So we have our strategies. All right.

152
00:30:16.260 --> 00:30:25.110
Now let's go to the special case where we have a transmitter Ray with em antennas and we're sending to us. Our to a single antenna terminal.

153
00:30:25.560 --> 00:30:43.020
By the way, it turns out that when you optimize the efficiency. The efficiency is the same in both directions, whether I'm transmitting from this array to this terminal or from this terminal to this array in any case for this case, you can get a closed form expression for the optimum.

154
00:30:44.040 --> 00:30:58.020
transfer efficiency in terms of this auxiliary parameter alpha, which in turn can be expressed in terms of elements of the impedance matrix and smaller. A alpha is the better off we are

155
00:30:59.460 --> 00:31:14.130
Or the alpha is always greater than or equal to one. So the closer alpha is to one, the closer our efficiency is to one. And if we have perfect coupling between the transmitter ray and this receiver.

156
00:31:15.360 --> 00:31:27.360
Then we get 100% efficiency. Now, I agree, the strategy. Remember that was whatever the transmitter does the receiver tries to pull maximum power out of its antenna.

157
00:31:27.810 --> 00:31:42.390
This has an even simpler expression for the efficiency alpha is always greater than or equal to one. So the greedy efficiencies never greater than one half. And so what I've done in this graph is just plot out the blue curve which is

158
00:31:43.140 --> 00:31:57.450
maximized efficiency as a function of this parameter alpha and the dotted red is simply the greedy efficiency which stops it one half. Where is for fault small enough alpha

159
00:31:57.840 --> 00:32:05.340
They maximize efficiency can go as high as you wish. With difficulty, of course. Alright, so

160
00:32:05.940 --> 00:32:12.960
This is this really is completes our discussion of the circuit theory of wireless power transfer

161
00:32:13.380 --> 00:32:27.750
And in a sense, you see that there's in one sense, there's nothing more to say about this. We've got this expression, this is this is universally applicable to any system of antennas. There's. So in one sense, there's nothing more to say about the problem.

162
00:32:28.080 --> 00:32:40.080
The function of electromagnetic theory viewed from this narrow point of view is simply to provide us with numerical values to fill in the impedance matrix, so that we can figure out how well we can do

163
00:32:41.190 --> 00:32:50.880
This of course is a gross simplification, but we need to now go to some electromagnetic theory to understand what's going on.

164
00:32:53.760 --> 00:33:14.820
With previously pointed out that conventional beam forming just conventional fed phased array activities are unlikely to solve the Long Range electrical wireless power transfer problem. So what's a particular interest to me is a topic called super directives city.

165
00:33:16.080 --> 00:33:28.560
This was originated by a bell labs researcher in 1943 Sergei shell Chernoff shell can off is also famous for having developed coaxial cable in the 1930s.

166
00:33:30.060 --> 00:33:44.250
And provocative title I learned about this in 1995 incidentally Jerry for skinny, of course, is very famous for his pioneering contributions to multiple antenna wireless

167
00:33:44.580 --> 00:33:54.090
On my first day at Bell Labs in 1995 I met Jerry and he told me about his my mo work. I thought this is the supreme invention.

168
00:33:56.100 --> 00:34:05.670
I'm at the right place here and Mike GANs wrote an internal memo in 1995 there was an appendix in it, which didn't

169
00:34:06.090 --> 00:34:21.360
Make it into the published version of the paper. But let me just read what the appendix was written entirely. But Mike ganz who was an expert in electromagnetic theory. So what are they saying, here we have a transmitting horn antenna.

170
00:34:23.220 --> 00:34:32.370
Low game located in outer space aimed at Earth has a huge you know maybe a 45 degrees being with okay

171
00:34:32.850 --> 00:34:49.530
Get this in principle, a one wavelength diameters super gang they they're using the term super game here not super directives it, but it's the same idea. It's possible for that receiver ray to receive virtually all of the power radiated by the horn antenna.

172
00:34:49.770 --> 00:34:58.320
So that's super directives it. And this seems very weird, among other things, of course, we know we have to have conservation of energy.

173
00:34:58.800 --> 00:35:06.750
So this receiver right can't pull more power out of the ether than the transmit antenna is radiating

174
00:35:07.110 --> 00:35:20.550
What happens. For instance, if you have other receive antennas around. Are they affected by this not at all obvious and it wasn't so obvious to me in those days. And now I want to try to impart my understanding of this topic.

175
00:35:21.450 --> 00:35:38.100
So, to make matters even more confusing super directives, it is sometimes confused with another phenomenon called super resolution. Well, the chiefs distinction is super directives, it is a physical thing and

176
00:35:39.240 --> 00:35:47.070
The idea is actually to put antennas and a transmitter a close enough together so that they interact

177
00:35:47.670 --> 00:35:58.410
Strong mutual coupling, now ordinarily we communication theorists love to think that antennas and an array or uncoupled makes life very easy and simple.

178
00:35:58.830 --> 00:36:10.620
But today, in fact, our and, in particular, if they're made close together. All right. The super resolution method is just a mathematical thing, the whole idea is that you you have

179
00:36:11.370 --> 00:36:29.520
You have samples from an antenna array, say, a linear array of finite length and you know that classically, the angular resolution is equal to the wavelength divided by the linear aperture of the array non dimensional quantity and

180

00:36:30.690 --> 00:36:43.650
Longer the array, the finer the being, well, the whole idea of super resolution is you you pretend that the propagating field spatially band limited nice twist.

181
00:36:44.010 --> 00:36:56.370
Interval a half wavelength. Now, in fact, it really isn't because you have evanescent waves in the near field that actually go faster than that implied rate which is two pi over lambda

182
00:36:58.380 --> 00:37:04.470
But if really were mathematically a band limited field, then it's what's called an analytic function.

183
00:37:04.740 --> 00:37:17.640
And in fact, by measuring this field over a finite interval, I could in fact extrapolate the field in both directions as far away as I wanted. So in effect, starting with measurements from a small array.

184
00:37:18.390 --> 00:37:28.260
I could mathematically extrapolate and infer what I would measure if I had a really large array which would have much finer angular resolution.

185
00:37:28.560 --> 00:37:44.580
Super directives it however relies on a physical effect mutual coupling among antennas. And in fact, if I were doing synthetic aperture radar. I could, in principle, use super resolution, but not super directives, so these are distinct things

186
00:37:46.260 --> 00:37:56.340
So let me just give an example of a super directive scenario. So here I have a linear array of elements.

187
00:37:57.060 --> 00:38:13.680
Space, even the D apart and on the axis of the array, hence end fire. I have a receiver antenna. Alright, so this whole system is described by a partitioned impedance matrix. And here is here is the

188
00:38:15.480 --> 00:38:16.350
Here is the

189
00:38:17.880 --> 00:38:26.160
Am I am impedance matrix that describes the mutual coupling among the transmit antennas were only interested in its real part.

190
00:38:26.580 --> 00:38:37.560
And here is the propagation vectors. The M one between the AM antennas and the single receiver and then the self impedance of each antenna is just one

191
00:38:38.190 --> 00:38:53.040
And what we want to do is we have a power total power transmitted power constraints, subject to that constraint we

want to maximize the open circuit voltage on the receive antenna. So here we're not trying to transmit power. We're just trying to

192
00:38:53.790 --> 00:38:57.960
Transplant or impart the biggest signal to the receiver antenna.

193
00:38:58.830 --> 00:39:12.360
Of if you ignore mutual coupling. Everybody knows this is like a matched filter. It's called maximum ratio being farming underwater acoustics. People call it time reversal being forming

194
00:39:12.780 --> 00:39:20.790
And in fact, my optimum transmit current is just the conjugate of the propagation vector normalized to get the

195
00:39:21.780 --> 00:39:28.560
The power of to conform to are transmitted power constraint. So what this gives us is a

196
00:39:29.370 --> 00:39:42.180
open circuit voltage who's on the receive antenna who square is just proportional to em, the number of transmitter antennas. So this is the usual been farming game for normal activities.

197
00:39:42.510 --> 00:39:52.290
Super directive being farming. Well, we have to actually take into account the interaction among the transmit antennas. So instead of some of the currents being

198
00:39:52.770 --> 00:40:01.800
Equal to p zero instead, we have this quadratic form in the terms of the real part of the December am impedance matrix.

199
00:40:02.220 --> 00:40:08.970
And so this looks like a colored noise matched filter type of problem. It's mathematically, the same

200
00:40:09.390 --> 00:40:18.510
Guess what, for this configuration we get a beam forming game that's proportional to M squared, instead of em. So basically of

201
00:40:18.990 --> 00:40:28.350
Super dirt activity increases in this example been farming game from n to n squared, not so obvious. This happens. Let's just see numerically.

202
00:40:28.980 --> 00:40:31.260
So we have an eight element array.

203
00:40:31.740 --> 00:40:46.530

Okay, and what we're plotting here is the maximum ratio being farming gain the dash curve as a function of the antenna spacing and wavelengths and then the solid curve is the super directive and 10 again.

204
00:40:46.860 --> 00:40:58.980
We started half wavelength and both are equally good giving a beam forming gain of eight, which is the number of antennas we decrease the antenna spacing.

205
00:41:00.090 --> 00:41:15.780
Maximum ratio does a little bit better for a while and then head south, and by the time we're here. Guess what these and eight antennas are almost on top of one another and doing no better than a single antenna. So here, maximum ratio is giving a beam forming gain of one

206
00:41:16.140 --> 00:41:28.740
It says, if we had only one antenna, whereas super directive array is giving M squared almost 64. So let's look at another

207
00:41:29.610 --> 00:41:40.830
Scenario. So again, we have a linear array, but now the receiver is broad side to be array normal to the array axis. So here we have on the think on the line.

208
00:41:41.430 --> 00:41:55.920
X y equals zero. We have array on the Z axis. And then the receiver is now normal to be array normal to this line, guess what we get absolutely no super directives city whatsoever.

209
00:41:56.880 --> 00:42:09.300
Decreasing spacing between antennas just makes things head south we did this for two up to 32 antennas, so. So what's going on here. How do we explain super direct activity.

210
00:42:10.200 --> 00:42:23.160
Well of in the limit as these antennas. The spacing goes to zero. These eight antennas are almost on top of one another. How should we utilize them look just consider two antennas.

211
00:42:24.000 --> 00:42:33.660
If we move to antennas very close together, what can we do what we can always express the two currents in terms of the some of the two parents and the difference of the two currents

212
00:42:33.960 --> 00:42:39.900
Well, some itself. You know, we may want to use it but but doesn't do anything that a single antenna can do

213
00:42:40.260 --> 00:42:53.610
But the difference of the current if we make the magnitude of the currents of make the two currents equal and opposite with a magnitude inversely proportional to the spacing, then it's like a spatial derivative

214
00:42:54.060 --> 00:43:06.090

And in fact, we can think of a short dipole as equivalent to a two elements super directive array because of what is the short dipole. We effect, we have two

215
00:43:06.570 --> 00:43:13.560
Sources of charge equal and opposite and sign that are very close together and they're magnitudes.

216
00:43:14.190 --> 00:43:31.080
Are inversely proportional to the spacing. That's just a hertz and dipole. So if our current distribution as a function of ZZ is the position along the axis of the array in the limits. When the antennas are on top of each other is just a

217
00:43:32.100 --> 00:43:45.030
Superposition a linear combination of spatial derivatives of a point source of a direct delta function. So we're doing funny things here. It's also telling us that guess what

218
00:43:45.930 --> 00:43:55.140
The closer we make the antennas to super direct activity. We're actually feeding numerically bigger and bigger currents into the antennas.

219
00:43:55.890 --> 00:44:04.470
So let's give two interpretations mathematical of, well, what's the mathematical interpretation you look at this

220
00:44:05.040 --> 00:44:17.370
Real part of the mutual impedance matrix and my my transmitting antennas. Look at the Eigen space. Find a subspace of the Eigen space that has very small eigenvalues

221
00:44:17.880 --> 00:44:27.420
Those modes you can drive with very large numerically large currents without expending much real power. It seems like a good thing.

222
00:44:27.840 --> 00:44:45.390
At the same time, we want this Eigen space to contain at least some of the energy of the provocation vector. So, if we can do this, then we can get super direct to 50 so it's really just a eigenvector eigenvalue explanation. That's a physical explanation.

223
00:44:46.440 --> 00:44:50.040
So up was shown in

224
00:44:51.360 --> 00:45:02.580
By the mathematician Herrmann vile who he his career. I think culminated at Institute for Advanced Study in Princeton, but in 1919

225
00:45:03.030 --> 00:45:16.230
Mile showed that a spherical wave due to a point source externally can be can be expanded in terms of playing waves

will superposition of playing waves, not at all obvious result.

226
00:45:16.650 --> 00:45:25.830
And by extension, a distribution of sources and some finite volume. So in this case, our element antenna array.

227
00:45:26.460 --> 00:45:35.010
Externally, we can represent the total field due to these mm tennis as a superposition of plane waves well

228
00:45:35.760 --> 00:45:44.190
In the direction we're creating very large currents that very rapidly over z.

229
00:45:44.880 --> 00:46:01.230
So the wave number the spatial frequency of associated with the radiating field, or at least some parts of the radiating field has a wave number greater than K K being two pi overland of the inherent

230
00:46:02.160 --> 00:46:12.720
propagation constant for the medium. Now some of squares of playing with of wave numbers has to add up to case squared. The scenes that transverse Li

231
00:46:13.170 --> 00:46:21.810
X and Y wave numbers have to have a square which is negative. So these become imaginary valued.

232
00:46:22.380 --> 00:46:31.470
Well, if a wave number the plane wave is imaginary valued than the plane wave to case exponentially fast in that direction.

233
00:46:32.310 --> 00:46:39.870
And carries only reactive power. So, this explains why we're able to get this extra gain in the z direction.

234
00:46:40.260 --> 00:46:53.520
Are we're we're external field is made up in part of these super wave number of playing waves, the super playing with number of playing waves don't radiate transverse Lee. So it's a bit like

235
00:46:54.090 --> 00:47:07.290
Taking a squeezing a tube of toothpaste. It shoots out the end and the z direction. Okay, this explains also why that broad side operation example that we showed here.

236
00:47:07.950 --> 00:47:22.170
Didn't display any super direct diversity because in the direction we wanted to go putting the antennas close together was creating evanescent waves which were decaying exponentially fast towards the receiver and carrying

237
00:47:23.100 --> 00:47:30.870

In part, old a reactive power. So this is what's going on to interpretations. Let's consider just a

238
00:47:31.320 --> 00:47:47.610
Simple power transfer example. So now we have a 10 element antenna array linear array. Again, this is n fire operation, our receiver is five wavelengths from I believe the center of the antenna array.

239
00:47:49.440 --> 00:47:58.200
AND NOW WE WHAT WE'RE DOING HERE IS WE DID OUR SUPER directive calculation, but we assumed that the

240
00:47:59.010 --> 00:48:14.100
transmit antennas had some internal Oh, Mike resistance and that the ratio of the omega resistance to the radiation resistance was variously 110 to the minus two, all the way to 10 to the minus 2012

241
00:48:14.880 --> 00:48:31.710
So 10 to the minus 12 basically means that there's no internal resistance within my and transmit antennas that could actually be achieved in theory with superconducting transmit antennas and what we've done again is plotted out the

242
00:48:32.910 --> 00:48:53.730
power transfer efficiency. Okay, as a function of the antenna spacing for these. What is it's seven cases. And we started half wavelength. And we see that basically for each one of these

243
00:48:55.320 --> 00:49:09.510
Specified internal radiation our internal omega rate resistance. There are some optimum spacing beyond which making the spacing shorter makes, of course, the efficiency decrease

244
00:49:09.810 --> 00:49:21.150
And by the time we're up here. We're, we're basically getting about five times the transfer efficiency that we got when we had halfway link spacing so

245
00:49:23.190 --> 00:49:27.750
This is, this is a toy example, but it does illustrate some points.

246
00:49:29.190 --> 00:49:38.010
So traditional problems with super direct Tiffany at this was known, even by shell cut off. So as I said,

247
00:49:38.520 --> 00:49:51.630
As the antennas get closer together, we're trying to create spatial derivatives, effectively, meaning that the currents we drive these antennas with grow essentially without found

248
00:49:52.350 --> 00:50:08.550
And this is associated with the fact that are in real part of her impedance matrix is becoming near singular as the spacing shortens okay this of course sets should set some alarm bells off. It does, in fact, what I was doing.

249
00:50:09.660 --> 00:50:15.840
This calculation, Matt. Matt wouldn't let me go to any shorter spacing.

250
00:50:16.440 --> 00:50:31.020
And I tried to of course we're dealing with a templates matrix. I tried all of the fancy templates matrix algorithms sure algorithm and so on, that were developed 3040 years ago. None of them did as well as chill esky factorization so

251
00:50:32.490 --> 00:50:44.100
What's the other problem. Well, again, these antenna currents are becoming enormous are real radiated power is under control, but the reactive power.

252
00:50:44.910 --> 00:50:54.720
Is huge and the huge currents also are responsible for internal omit losses. Unless, of course, we have superconducting antennas.

253
00:50:55.230 --> 00:51:01.140
And we have a huge reactive field in the vicinity of the antenna array.

254
00:51:01.440 --> 00:51:16.050
Is that so bad. Every quarter cycle you feed reactive power out into the ether. The next quarter cycle, it's pulled back into the antennas, of course, at some point, the electric field intensity might get so great that the air is ionized.

255
00:51:16.590 --> 00:51:27.960
And of course with any sort of problem with a dividing by a matrix that's nearly singular, you have some extreme, extreme sensitivity issues that need dealing with. Okay.

256
00:51:29.580 --> 00:51:40.560
With all lapse of the question then is, how can we make super direct to the practical. So I've mentioned superconducting antennas.

257
00:51:41.850 --> 00:51:51.360
Possibly metamaterials new mine. Oh configurations. So people are talking about various forms of my mo holographic my mo.

258
00:51:52.680 --> 00:52:03.240
Intelligent reflecting surfaces. Another variation basically surrounds the user or users with antenna array. So if I'm inside of an office.

259
00:52:03.630 --> 00:52:22.290
Room. I could conceivably have the floors ceiling and walls covered with conformal antenna array. So, or if I'm in a New York City, there's this canyon of skyscrapers. I'm surrounded on all four sides effectively so

260
00:52:23.400 --> 00:52:30.060
If you think about and all of our experience with wireless or most of it wireless communications, it's the opposite.

261
00:52:30.360 --> 00:52:43.500
We have antenna array. Things are going outwards. But here are the antenna arrays around the human or users and so that it's a totally different configuration. I'm not sure we really understand that very well.

262
00:52:44.760 --> 00:52:51.510
We want robots in a factory. What if you made this factory with copper wall ceiling and floors.

263
00:52:53.130 --> 00:53:03.180
So this is now totally different from free space propagation. It's a highly reverberant propagation environment has some advantage.

264
00:53:03.570 --> 00:53:17.580
Interior is isolated from exteriors so there should be no spectrum licensing issues as long as this is a solid copper box. Nothing's going to radiate outside. I don't have to pay any attention to spectrum licensing.

265
00:53:19.320 --> 00:53:33.240
Because there are no near far effects so one over our attenuation doesn't really work if if I send out source and expanded and playing wave each plane way flies all over the place and creates

266
00:53:34.020 --> 00:53:45.660
Playing ways from all sorts of angles. So there's many degrees of freedom and I just considered supposing I put two antennas simple antennas a transmitter and a receiver antenna in this box.

267
00:53:46.920 --> 00:54:00.900
Let's suppose neither antenna has any internal resistance then without doing any super directive stuff I have 100% power transfer efficiency between these two antennas so

268
00:54:02.310 --> 00:54:04.140
They're there possibly other things.

269
00:54:05.250 --> 00:54:18.390
So let's go back to this philosophical philosophical issue about mathematics. And what does it really count for obviously it's a tool we use and must use

270
00:54:20.190 --> 00:54:42.120
But here's a great example from the year 2008 a group of professors and students at MIT did this experiment, they had this transmit coil which was driven by 10 megahertz continuous wave signal over here is similar coil and see it's lighting up a light bulb. This is several meters.

271

00:54:43.230 --> 00:54:51.300
The wavelength is 30 meters. So we're operating about less than a 10th over wavelength receiver from transmitter

272
00:54:52.290 --> 00:55:09.150
The world was surprised that they were able to transmit 60 watts of power with 40% efficiency and this system of coils is basically nothing but an open an Air Corps transformer well

273
00:55:10.920 --> 00:55:16.890
An ordinary iron transformer is designed so that the coupling coefficient between

274
00:55:17.520 --> 00:55:28.170
Which is the percentage of magnetic flux generated by the transmit coil or a primary coil that's intercepted by the secondary coin was like 99%

275
00:55:28.440 --> 00:55:35.760
Here the coupling coefficient was a point 2%. And so how are they able to get such efficiency. Well, it turns out

276
00:55:36.030 --> 00:55:54.240
That the cues, the ratio of the reactants of the primary coil to its resistance. That's cute puppy and similarly for the receiver Q as both these cues were about 1000. And if you look at this formula. Yes. Your take square root of 1000 times 1000 times point 002 and guess what you get.

277
00:55:56.220 --> 00:56:03.540
You get to the number two. And when you substitute in here and square it and so on. Yeah, you're getting 40% efficiency.

278
00:56:04.050 --> 00:56:13.440
So they publish this and Annals of physics, which was the journal than Einstein published his most famous papers and

279
00:56:14.280 --> 00:56:25.050
As I say, the world was surprised why should the world have been surprised after all the somebody 100 120 years ago had thoroughly worked out all of the mathematics for

280
00:56:25.590 --> 00:56:35.100
This problem fully understood. So the mathematics was in place, but people really didn't understand its implications. So once again.

281
00:56:35.370 --> 00:56:41.460
Just because we have the mathematics for a problem that doesn't close the door on innovation and invention.

282
00:56:41.910 --> 00:56:54.060
And by the way, if you look at this expression for efficiency which is equivalent to the one that I presented earlier in the talk. If I let the primary Q go to infinity.

283
00:56:54.480 --> 00:57:11.460
Up the secondary Q not guess what my efficiency goes to one. This means that if you believe this expression and of course there are some coffee ups. If I make the primary coil super conducting I should get close to 100% transfer efficiency. OK.

284
00:57:12.690 --> 00:57:14.280
So the final thing.

285
00:57:15.660 --> 00:57:17.400
I want to simply

286
00:57:18.420 --> 00:57:36.870
You need to know electromagnetic theory. If you're going to, or at least have a working knowledge of it. If you're going to contribute to these topics and wireless power transfer and of course all of us all, all electrical engineers. I've been exposed to this and undergraduate school but

287
00:57:38.580 --> 00:57:48.390
It's of course a fact of life that most people, most communication theorists even wireless communication theorists most signal processing researchers

288
00:57:48.720 --> 00:58:04.350
Really are not comfortable with electromagnetic theory. And I think there's a better way to teach it than the way all of us were taught this subject. So this spring. I've been giving a new course linear system approach to wave propagation

289
00:58:05.370 --> 00:58:15.270
Let me. Don't scare too many people by these old formulas are bringing back old nightmares. But look, here's the traditional physicists approach.

290
00:58:15.990 --> 00:58:23.850
The electric electromagnetic field comprises an electric field three component vector magnetic field. Okay.

291
00:58:24.810 --> 00:58:45.690
We produce this up by a transmitter. In this case we model our system of transmitters, just as a electric current density source expressed in amps per meter square. This is distributed in time and space here are the four Maxwell's equations, driven by the electric current density

292
00:58:47.640 --> 00:58:58.320
What does a physicist do physicist expresses the NIH fields in terms of a scale or potential fee a vector potential a these on intuitive.

293
00:58:59.490 --> 00:59:07.110
Really non physical relations and an extra condition on the vector potential

294
00:59:07.740 --> 00:59:19.860
And you substitute these expressions into Maxwell's equations and simplify and you find you get for uncoupled wave equations, driven by the

295
00:59:20.370 --> 00:59:33.780
Electric current density of physicists likes to solve the wave equation by method of separation variables and often in spherical coordinates which spherical coordinates have their uses

296
00:59:34.140 --> 00:59:39.060
But if you want to figure out what does a linear array or a

297
00:59:39.840 --> 00:59:53.580
Or a planar array on a Cartesian grid. How does that affect the electric and magnetic field, you lose all insight and signal processing insight by working in spherical coordinates. I don't like them. Oh, there

298
00:59:54.360 --> 00:59:59.160
You need them for some things. So what's my approach Maxwell's equations, but now

299
00:59:59.790 --> 01:00:10.020
Thing to notices Maxwell's equations can be interpreted as descriptive of a linear space time and variance system. What do we mean

300
01:00:10.710 --> 01:00:18.660
When we have an input to the system, which is this electric current density and we have an output, which is the EH fields.

301
01:00:19.380 --> 01:00:28.050
Okay, if we delay. If so, if we compute UNH in terms of our particular j. Now if we delay this

302
01:00:28.770 --> 01:00:38.370
Source in time by 10 seconds we get the same solution for electric and magnetic fields delayed by 10 seconds if I move this source.

303
01:00:38.910 --> 01:00:48.600
Say 20 meters North northeast and guess what I get the same solution with the EH field shifted by the same amount. And space.

304
01:00:48.990 --> 01:00:59.820
So this means we can have, however, complicated it is. We can express the solution for E and H fields as a spacetime convolution in terms of this

305

01:01:00.030 --> 01:01:07.560
Impulse response, which is a six by three matrix and technically it's called a greens function, but you can just think impulse response.

306
01:01:08.190 --> 01:01:24.690
Well, if this is a convolution in space and time. That's a multiplication and temporal frequency and spatial frequency. And so how do we find this space of the type role spatial frequency response in the system. We simply take

307
01:01:26.400 --> 01:01:33.210
four dimensional for a transformed space time for a transform of both sides of Maxwell's equations.

308
01:01:34.170 --> 01:01:48.600
And we do that and now we're entirely in the frequency wave number domain we have let's see three and three is six on knowns. We have seven unknowns and we have eight equations here.

309
01:01:49.110 --> 01:02:00.420
And 15 minutes of time, you can actually get an explicit closed form solution for the eth fields in terms of the transform of the electric

310
01:02:01.380 --> 01:02:13.620
Current density. This is closed form no approximation and now thing to focus on is all of the wave propagation action is in this denominator and

311
01:02:14.280 --> 01:02:22.440
Guess what we suppose we just told temporal frequency and k x and Ky fixed and just consider this as a

312
01:02:23.010 --> 01:02:44.880
Linear shifting variance system with transform. CASEY We can factor this denominator polynomial into two simple polls we extract the residues of the polls and with some work we actually get a very fundamental result that the source distribution is confined to some

313
01:02:46.110 --> 01:02:49.410
Compact volume region and space.

314
01:02:49.860 --> 01:03:06.480
And exterior to resource distribution. I can rigorously expand the electric and magnetic fields, eh, in terms of plane waves of this form and some of the squares of the three wave numbers has to add up to k squared caving to pi overland

315
01:03:07.260 --> 01:03:15.300
Okay, so enough of this course. I think I've given you a bit of a flavor for how this can be done and it really

316
01:03:16.080 --> 01:03:30.000
Makes life infinitely easier and more insightful for both the signal processing researcher and the communication

theorist, I'm running over by about five minutes, but this is the last slide. And I think my conclusions probably are pretty obvious.

317
01:03:31.350 --> 01:03:42.900
There's just a enormous potential impact for wireless power transfer, but we don't know yet how to transmit power wirelessly 100 meters or more

318
01:03:44.130 --> 01:03:50.910
We've got to have more bold and risky research, it has to be both bold and has to be risky. Okay.

319
01:03:52.800 --> 01:03:55.980
This isn't going to happen on its own. Unless, of course, we have some

320
01:03:57.090 --> 01:04:04.800
Alone inventor or inventor getting some tremendous intuitive insight and actually

321
01:04:05.880 --> 01:04:18.930
producing some prototype that can transmit wireless power 100 meters. It isn't impossible, but as researchers, of course you know we operate in a different way.

322
01:04:21.090 --> 01:04:34.050
And a lot of our people really could stand to acquire a real working knowledge of electromagnetic theory. And I think there's a better way than the way we learned it.

323
01:04:34.710 --> 01:04:48.930
I think virtually all of us learned it in school and then this philosophical issue that you can have a complete mathematical description of a topic or a phenomenon, but that doesn't mean you really understand the phenomenon.

324
01:04:49.380 --> 01:05:08.400
And so there's still scope for discovery and invention, and then just the final piece of wisdom from Lord Kelvin back in the 1870s, so I'm going to stop here. And I'd like to take some questions. And again, sorry for running over a little bit.

325
01:05:11.040 --> 01:05:15.750
Thank you, Dr Mirza thank you for that excellent lecture, you know, providing us with the

326
01:05:17.190 --> 01:05:26.760
theoretical background how research and this area has progressed through the years and and then your thoughts on you know what needs to be

327
01:05:27.450 --> 01:05:43.740
Done to make it practical. So yeah, so thank you. Great, great presentation. So I would invite our participants to use the q&a feature to pose the questions there. So there are some of them. So I'll start off with

328
01:05:44.760 --> 01:05:50.280
The first one. So, so, you know, so you have talked about, you know, the how to make

329
01:05:52.080 --> 01:06:07.410
Wireless transfer practical. So, so this is a question from George Murkowski says, What can you say about wireless wireless power technology that Tesla has developed or talked about

330
01:06:09.390 --> 01:06:15.930
Right. So Tesla, of course, famously talked about wireless power did some demos of it.

331
01:06:17.610 --> 01:06:35.790
I honestly can't say too much. Because my understanding is that he has a lab burned down disastrously at some point late in his career and his notes were lost and he didn't publish papers for the most part, so precisely what he did.

332
01:06:37.620 --> 01:06:39.750
You know, I'm not a quick to say

333
01:06:41.190 --> 01:06:53.430
So he probably would not have been surprised at all by the experiment that the group at MIT did in 2008 and in fact may well have done similar experiments.

334
01:06:55.410 --> 01:06:56.010
Thank you.

335
01:06:58.770 --> 01:07:04.230
Next question is from Lisa so so we talked about, you know, when you are looking at

336
01:07:05.550 --> 01:07:13.200
Wireless transfer the medium is here. So what happens when we switch the fluid from air to water.

337
01:07:14.820 --> 01:07:16.350
That's a real good question.

338
01:07:18.510 --> 01:07:31.440
Of course underwater community work is exceedingly difficult because do underwater sonar or underwater acoustic communications.

339
01:07:31.920 --> 01:07:38.790
You can't ignore the details of the wave propagation, because the ocean is not a uniform medium, you have

340
01:07:39.750 --> 01:07:46.920

A basically sound speed and density are affected strongly by salinity and temperature and

341
01:07:47.730 --> 01:08:05.460
So there you will always have to take into account the and homogeneity or at least the stratified layering the if you're trying to do. If you're trying to do wireless power transfer underwater. One of the limitations, you run against is that in shallow water.

342
01:08:06.540 --> 01:08:27.810
If you make the sound intensity too strong. The dynamic pressure magnitude exceeds the hydrostatic pressure that the depth at which you're working total pressure goes negative. And if you have a unless your fluid is absolutely pure with no dissolved

343
01:08:28.890 --> 01:08:43.350
Dirt particles or air of fluid generally cannot support negative pressure at tears apart kava tastes. So, this in fact. So that's one difficulty with underwater.

344
01:08:44.520 --> 01:08:46.080
wireless power transfer

345
01:08:51.600 --> 01:09:01.530
Next question I have is from Shanker buses all read the question to you, it says you have generalize the circuit theoretic problem of broadband matching

346
01:09:02.040 --> 01:09:12.450
Of Harvard Carlin and Daniel to pass in multiple routes in the context of antennas. The question is, what about the inverse

347
01:09:13.050 --> 01:09:31.860
Circuit and nothing synthesis problem. That is how can one design the antenna array from specifications. Can one drop possible multiple circuits synthesis theory set as the old classical papers from on on your side on multiple passive subscriptions.

348
01:09:33.270 --> 01:09:43.620
That's a good question. So. So remember how I formulated transmitting power from one array to another array, I

349
01:09:44.940 --> 01:09:51.960
I basically formulated in terms of the transmit current, current vector and the receive current vector

350
01:09:52.380 --> 01:10:14.040
And did my power optimism or efficiency optimization jointly over the two vectors of currents now so I paid no attention to the load and cadences that are impedance network, but that one tax on to the receive antennas yet of course to make a functioning.

351

01:10:15.480 --> 01:10:25.260
Our transfer system, I would have to do that. So I would have to take my end receive antennas and I'd have to connect them to a passive

352
01:10:26.040 --> 01:10:36.630
Linear network of resistors. I'm sorry. No, you don't want resistors, they're going to dissipate power capacitors and doctors and transformers and

353
01:10:37.380 --> 01:10:47.190
So there's a whole science. This would be in you lose book. And of course in classical books by amps Gilman from 60 years ago or more

354
01:10:47.670 --> 01:11:11.370
That tell you how you can actually synthesize a passive network to have some desired impedance versus frequency or transfer characteristics. So the answer is yes, you would have to draw on a lot of this classical network synthesis theory to do build a practical wireless transfer system.

355
01:11:14.580 --> 01:11:29.310
Thank you. So next question is by Kenyan zoom. So, yes. What feedback control would feedback that will be useful to increase the bulk of our calls for efficiency. That's a great question.

356
01:11:30.390 --> 01:11:33.480
If, if the both ends of the link

357
01:11:34.950 --> 01:11:44.820
So the transmitter transmitter and the receiver if they both know the complete impedance matrix, you know, with 100% accuracy, then

358
01:11:45.480 --> 01:11:56.100
feedback control is not going to help any because you can just open loop. Set the transmit and receive currents. All right, practically speaking, of course. And remember, I said that

359
01:11:56.430 --> 01:12:05.610
If you'd want to do super directives it. It's a very sensitive. That is the optimum currents are very sensitive to the assumed

360
01:12:06.210 --> 01:12:17.100
Impedance matrix. Yeah. Then some tour feedback scheme could help. So roughly speaking, and I haven't spent any time looking at this problem.

361
01:12:17.730 --> 01:12:30.600
You have a CSI acquisition problem of two types of CSI standing for channel state information, namely, you need to know all elements of this impedance matrix. So,

362
01:12:31.740 --> 01:12:40.620
So in addition to putting pilot signals into each of the transmit antennas and measuring the received

363
01:12:41.640 --> 01:12:45.120
Signal at the other antennas up

364
01:12:46.320 --> 01:12:56.520
To get between the transmitter and receiver Ray, you need to do it internally in the transmitter ray in order to infer the mutual coupling among the antennas.

365
01:12:59.010 --> 01:13:17.430
Next question. Next question. So this is from Bertrand hope the hope world. So the exhaust was the MIT experiment. An example of super directory super direct devotee productivity or inductive mutual copying or is it the same thing.

366
01:13:19.020 --> 01:13:27.270
Good question. I don't think I don't think of it as an example of super directives, it, it was inducted mutual coupling.

367
01:13:28.740 --> 01:13:48.750
If you look at one of the papers from this MIT group. They called it resonant evanescent wave coupling. And so, you know, one way to analyze their system was to just as I did in the view graph you draw a circuit diagram. And this is a Air Corps transformer

368
01:13:50.220 --> 01:14:03.660
So, but you could do a full Maxwell's equation approach and have this as well on you. In the end, you should get the same answer. And remember, I said that whatever I do and transmit region externally.

369
01:14:03.960 --> 01:14:07.680
The field is expandable in plain wave. So this coil.

370
01:14:08.130 --> 01:14:20.790
Of transmit coil. Once I get away from that coil. I have a superposition of playing waves. Now this is extreme near field. So most of these playing waves, the strongest ones are evanescent waves and so

371
01:14:21.360 --> 01:14:31.680
What's going towards the receive coil is a bunch of evanescent waves that are decaying exponentially fast towards the receive coil.

372
01:14:32.040 --> 01:14:47.010
And nominally carry only reactive power toward the receive coil, but we're somehow frustrating them doing making them. These evanescent waves do something, contrary to their nature by transmitting power.

373
01:14:48.060 --> 01:14:58.980

The next question please. Thank you. Next question is from song friends asked, what do you think about simultaneous wire transfer and power trolls.

374
01:15:00.210 --> 01:15:02.070
It's a very good question. I mean,

375
01:15:03.120 --> 01:15:20.190
Potentially, you can do that. But let's try to think a little bit about this so super directives, it could be used for wireless communications, of course, the we're talking about sending saying milliwatts or 10s of millions swaps.

376
01:15:21.150 --> 01:15:33.600
Via wireless power, maybe a nano water a peek a walk for communication purposes. So is, you know, you're, you're really talking about nine orders of magnitude of

377
01:15:34.170 --> 01:15:43.170
Power that you're trying to transfer. Another issue is that nobody would ever use super direct activity for communications purposes, without

378
01:15:44.880 --> 01:15:57.930
First exhausting other measures. So you're obviously going to be using as much spectrum as you can 10 or 20 megahertz. All right, so any super directive.

379
01:15:58.620 --> 01:16:03.690
Stuff that you want to do for communication purposes. You've got to do over very broadband.

380
01:16:03.990 --> 01:16:15.750
And that's a very difficult problem. Because again, if you're going to design these passive networks, you have to do clever things. Now there's a strong frequency dependence and so

381
01:16:16.110 --> 01:16:26.970
It's very difficult design problem, in a sense, then wireless power transfer is an easier problem because we can make it happen just at a single frequency

382
01:16:28.110 --> 01:16:28.710
So,

383
01:16:29.790 --> 01:16:31.020
Next question please think

384
01:16:32.040 --> 01:16:42.000
The next one is apartment by retire or we just about you know that there is a book in northeast and any you which works on underwater communications and

385
01:16:43.440 --> 01:16:55.530
My next question is from Adam there was so it says, Should wireless transmission technology be made more efficient and practical for broad energy use.

386
01:16:56.310 --> 01:17:07.080
And if so, would such new technology require all electrical technologies like generators motors transformers to be redesigned to at least some degree.

387
01:17:08.250 --> 01:17:21.300
A good question. First of all, the previous comment. Yes, I know that underwater acoustics group at Northeastern they're really good people. In fact, it turns out that at MIT, my PhD advisor was Arthur baggers who started out

388
01:17:22.350 --> 01:17:27.990
Purely and he was a student of Perry then threes. So we started out in detection and estimation

389
01:17:29.070 --> 01:17:36.750
But then, over the years, he went into underwater acoustics. And so, at any rate, yes. So let's see.

390
01:17:38.730 --> 01:17:51.660
I'm not sure you wouldn't have to change the generators motors and transformers. I mean, let's face it wire copper wires can carry enormous amounts of power relatively easily.

391
01:17:52.920 --> 01:18:00.000
And first by using very high voltages and, you know, comparatively low currents, you get

392
01:18:00.960 --> 01:18:19.770
In a minimize your own mic losses. So I don't think we want to abandon that any more than we would want to abandon optical fiber where we can afford to use it. So just as mobile wireless communications yes we we needed where we need it.

393
01:18:21.240 --> 01:18:36.150
Similarly, if we can make wireless power work and long range will use it where we need to use things like flying drones around or we want to have hundreds of robots in a factory that are untethered

394
01:18:37.680 --> 01:18:38.460
And. Next question.

395
01:18:39.840 --> 01:18:53.940
So next question is by hitesh product do you feel that going forward to 60 will will say small cell deployments. Is there ever going to be a possibility of our base station.

396
01:18:54.480 --> 01:19:03.240

To change our you eat and deliver data at the same but to chart. Let's see. I'm reading the question now. Do you feel that going forward to six g

397
01:19:03.780 --> 01:19:14.370
Was a small cell deployments. Is there ever going to be a possibility for base stations to char. Oh, so you want the base station to charge the UAE and to handle

398
01:19:15.390 --> 01:19:35.130
At the same time, that's an interesting thoughts of y'all. And I suppose conceivably, you could do it. But again, you know, you, I would tend to think that you would want to have a separate array at the base station one for transmitting power. The other for communications purposes.

399
01:19:36.870 --> 01:19:37.260
Thank you.

400
01:19:40.080 --> 01:19:44.880
Next question is by deep minutes he says they do you see as the next step.

401
01:19:46.110 --> 01:19:57.180
In the most innovation is needed in this space. So you talked about research, research, and he talked about even education to talk to, maybe, both from the research and the education side.

402
01:20:00.180 --> 01:20:02.760
So innovation needed in this space.

403
01:20:06.060 --> 01:20:12.510
I think the best thing is, of course, to get some multi disciplinary attention and thinking

404
01:20:13.170 --> 01:20:30.780
My experience over the years. Is there a lot of people who really understand wave propagation. Very well. People who can build microwave equipment incredibly skillfully make it work and do what they want it to do such people, however.

405
01:20:32.460 --> 01:20:45.060
With some a few exceptions, but mostly most such people do not understand communication theory do not understand Shannon theory. Conversely,

406
01:20:46.080 --> 01:20:56.820
Yes, here and there, you'll find a communication theorist or an information here is to understands wave propagation, but most dumped. And so we're really missing out because

407
01:20:57.720 --> 01:21:13.500
And in fact, I get the impression that when actual commercial will say five g six six G wireless equipment is built that it sort of divided up between two parties, you have the RF people who worry about the

408
01:21:14.310 --> 01:21:21.690
The RF electronics power amplifiers cables antennas mixers, that sort of thing.

409
01:21:22.170 --> 01:21:40.500
And then you have the people who designed the modulation schemes, the channel coding, that sort of thing. And it's as if these yes of course these two groups have to interact, to some extent, but at some level, they don't they proceed oblivious of the expertise that the other side has

410
01:21:42.240 --> 01:21:54.870
Thank you. So this is a follow up from Rita Rodriguez to a comments on via underwater communications, say, what do you think about trying to open underwater centers for communication.

411
01:21:57.240 --> 01:22:01.740
Well, I think that that's a very good example of

412
01:22:03.090 --> 01:22:14.970
I wish that I think that there could be great benefits if more electromagnetic wireless communications people talk to underwater acoustics people because the

413
01:22:16.440 --> 01:22:32.250
They both sides again would benefit from such a discussion, it's, I mean long other things you have you can have underwater acoustic situations where channels are doubly spread. For example, there

414
01:22:34.020 --> 01:22:43.860
They they're not really time in various systems they change rapidly over time and you know we're not used to dealing with such things.

415
01:22:45.000 --> 01:22:52.590
In most electromagnetic communications, we would like to assume that the channel is fixed long enough so we can estimate it.

416
01:22:53.010 --> 01:23:07.770
But a true time varying system I its nature is not even identifiable because if I send a training signal through it. Yes, I learned what it was in the past, but five seconds later, five, five hours later than I have changed.

417
01:23:09.030 --> 01:23:10.530
So I think that there again.

418
01:23:12.000 --> 01:23:20.640
Some cross disciplinary mixing and willingness to learn something about other fields can can really help us all.

419

01:23:23.910 --> 01:23:29.700
Knit lemon lemon asked, Are you writing a book or maybe sharing your lecture notes for your new coach.

420
01:23:30.720 --> 01:23:39.270
Okay, I plan to start writing the book this summer so that that's the short answer, and that's

421
01:23:42.750 --> 01:23:54.720
Let's hope that I actually can do some fairly fast writing I once again I my aim. And that book would be a relatively thin book, no more than 150 pages, but

422
01:23:56.520 --> 01:23:58.860
That was the way that I did my book with

423
01:24:00.660 --> 01:24:13.230
My comrades Erik Larsen home Yang, he clock know we set out to write a short book to completely get across the concept of massive my Mo and to try to

424
01:24:14.610 --> 01:24:18.690
Teach. Everything is simply as possible. So I'll try for that and just do

425
01:24:19.890 --> 01:24:32.640
It. Thank you. Thank you. When it is a comment, follow up comment by Shanker boss who's a says food mechanics and is inherently nonlinear so underwater communication is a different game.

426
01:24:34.380 --> 01:24:46.530
Well in ordinary sound pressure levels. That's correct. But yes, if you're starting to if the fluid is starting to cavity, then that's a, that's a tricky business right

427
01:24:49.740 --> 01:24:50.460
Well, I guess we've

428
01:24:51.510 --> 01:25:06.570
No more questions in the chat box right now. So, and we are almost coming to the end of the scheduled time so so want to thank you Dr Mirza for your

429
01:25:07.050 --> 01:25:23.760
Excellent presentation and also for the engaging Q any and so sharing your thoughts with us. So thank you once again. Well, thank you, everyone, and thank you for the great questions. And yeah, so I understand that this meeting is what is it 3pm. It's

430
01:25:25.260 --> 01:25:29.340
open to everyone. So I hope some of you show up with some even

431
01:25:30.600 --> 01:25:45.630
Even more questions. Thank you again. Yeah. Thank you. Thank you to all of those who joined and as as as dr Mirza setup encourage you to join at 3pm for any other you know questions and discussions human what Thank you everyone.