Oral History of Arogyaswami Paulraj

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Kapoor: On behalf of the Computer History Museum, I would like to welcome Professor Arogyaswami Joseph Paulraj for a conversation about his life history. My name is Uday Kapoor, and I am a volunteer in the Oral Histories Program at the museum. Professor Paulraj, a former Commodore in the Indian Navy, is currently a professor emeritus in the Department of Electrical Engineering at Stanford University. He was born on 14th of April, 1944, in Pollachi near Coimbatore, India. He joined the Indian Navy at a very young age and served it with distinction for 30 years. He received his bachelor's degree in electrical engineering from the Naval College of Engineering-Lonavala in India and his doctorate in electrical engineering from the Indian Institute of Technology in New Delhi. He served in India 'til 1991 where he pioneered the development of advanced military sonars. He also served as the founding director for three major labs in India: Centre for Artificial Intelligence and Robotics, Center for Development of Advanced Computing, and Central Research Labs of Bharat Electronics. He is the pioneer of a breakthrough wireless technology known as MIMO, multiple input/multiple output, that he developed at Stanford, which dramatically increases performance and capacity of wireless systems. MIMO is the core technology in the latest Wi-Fi and LTE systems crucial to local area and mobile wireless communications. Professor Paulraj founded Iospan Wireless Inc. in 1998, which developed the core 4G wireless technology and was later sold to Intel in 2003 and helped it launch its own push into WiMAX. He co-founded Beceem Communications in 2003, which became a leader in 4G chip sets. Beceem was acquired by Broadcom Corporation in 2010. Professor Paulraj was honored with numerous national awards in India, including the Padma Bhushan, Ati Vishisht Seva Medal, and the VASVIK Medal. An IEEE fellow, Professor Paulraj has been honored with the most prestigious global technology awards, the IEEE Alexander Graham Bell Medal in 2011 and the Marconi Prize in 2014, for his pioneering contributions to the telecommunications industry. So with that, we will start our conversation with Professor Paulraj. Welcome.

Paulraj: Thank you.

Kapoor: I'd like to start with your early life. I know you were born in 1944 in Pollachi near Coimbatore, Tamil Nadu. I guess at that time, it was in Madras presidency under the British Raj; and India was not yet an independent country. And your parents, I read: Sinappan Arogyaswami and Rose. You are one of six children. So maybe you can give me your views of your childhood.

Paulraj: Right. Pollachi was a small town. And soon after I was born, my father joined the Indian Navy, a profession that I later followed into. He was often on transfer, moving between ship and shore jobs, and the family, to give the children some stability in schooling, was sometimes left behind in a family station – meaning cities / towns with schools I grew up going to school in Coimbatore and later in Cochin. We were a large family. I certainly had a very happy childhood. Around the age of 11, I was finally was sent to a boarding school called Montfort for my high school, Montfort was in a hill town called Yercaud and I spent four happy years before graduating from there 1959.

Kapoor: So I read that you were always the top student; you always topped the class. That's very nice to know. So the various places that you went to school, like you mentioned Cochin, was probably because your father had to move around--

Paulraj: Yes, I was easily the top student in Math and Physics. At Montfort, I was taught Algebra, Trigonometry and Geometry but no Calculus. There were also no books in the library on Calculus. I tried to figure out how calculus worked on my own, and I got a hint from a book on log tables that listed a few calculus formulae. One problem I remember working with diligence, though unsuccessfully, was to prove that Newtons laws of gravity led to elliptical orbits of planets. While at Montfort, Russia had launched the Sputnik and the space race was on. A couple of Russians (or just Europeans?) had shown up in Yercaud, a sleepy hill town, and there were rumors in the school that I was a target of a kidnapping to be put to work on their space program, I never believed those rumors.

Kapoor :I read that you were in a pre-university in 1960 for six months, right?

Paulraj: Right, I finished high school in end 1959, but it wasn't qualification enough to get into degree college. I needed one prep year for college and so I joined a pre-university course at Loyola College in Chennai in mid-1960. I was very interested in Math and Sciences but had a poor understanding of the educational opportunities available. My father, though a Naval officer, was also not aware of career paths that could have leveraged my talent. The IITs (India's premium engineering schools) were just being started .and I would probably have discovered them while at Loyola and joined one after thst.. However, I got side tracked and joined the National Defense Academy (NDA) in Dec. 1960 well before completing the Pre-University course. My ignorance.

Kapoor: OK

Paulraj: In March 1960**,** I had sat for NDA exam on a whim and qualified easily. However, I did not consider an armed forces career seriously because of academic interests. My father felt that NDA was a good opportunity, but in no way forced me. NDA was also completely free and we were a large family with limited resources. As it turned out, I went to Poona (now Pune) for my NDA Medical Board exams and took the opportunity to visit the NDA near Poona. I was duly impressed by the majestic grounds and the layout of the Academy and my hesitation about an armed forces career melted and I joined the Academy in early 1961.

Kapoor: NDA was usually a very tough exam to get into that from what I remember.

Paulraj: Yes, the exam and the three-day interview and medical boards was a high bar those days.

Kapoor: And of course, you topped the class.

Paulraj: Yes, at the NDA, I was again easily the top cadet academically and <laughs>, clearly it was unusual for someone like me to be at the Academy with its emphasis mainly on sports and drilling. Some of NDA faculty would point this out to me. But it seemed too late to reverse course. And I made it to the top position - Academy Cadet Captain.

Kapoor: This is in Khadakvasla. And you finished your training in 1963 I believe--

Paulraj: Right.

Kapoor: And then the engineering training from 1964 to '68.

Paulraj: That's correct.

Kapoor: Then you were commissioned in 1965.

Paulraj: Started as Sea Cadet, then Midshipman and then commissioned as a Sub-Lieutenant in 1965. The initial training period of two and half years was on basic subjects like math, mechanics, electronics, drafting and carpentry etc. And then it became more Navy specific – sonars, radars, fire control, ship power systems etc. I was interested in more fundamental theory and tutored myself in subjects like control systems, information theory and signal processing. The college. Library had very few advanced books and so I bought some in Bombay and, visited TIFR's vast library. I was again the top student through these years. The training program, quite understandably, did not merit a B.E. degree. However, many years later, the Govt. of India decreed that the training I received was equivalent to a B.E. degree. I think that was done to help with post-retirement employment opportunities.

Kapoor: Okay. Yes, I remember reading about some of your comments later that when you went to IIT-Delhi that you finally went to a real university. <laughs>

Paulraj: That's correct, during my training, I didn't have the opportunity of accessing a real library with advanced books and research journals.

Kapoor: So in the 1960s, I understand that the Indian Navy had been experiencing some difficulties with the sonar, especially with the 170B sonar performance.

Paulraj: Yes BARC had started on a sonar project perhaps around 1969

Kapoor: And I understand-- and we can spend some more time little bit later as well-- that the Bhabha Atomic Research Centre was asked to improve some of the signal processing. So were you exposed to that at some stage?

Paulraj: I did not know about the BARC project till Dec 1971 when INS Kukhri was sunk. The BARC project started in 1969, I think, I was at IIT Delhi working on my PhD, between 1969 to 71.. The BARC project began with a young scientist Mr. Phadnis from Bhabha Atomic Research Centre visiting Italy on a nuclear instrumentation project. There his host told him that the same instrument could be also used in sonar systems. Lieutenant Jain had somehow met Phadnis and they managed to overcome bureaucratic hurdles and launch a project to improve Sonar 170B, the Navy's top sonar. BARC equipment was installed on INS Kukhri when it went on patrol during the 1971 war. Kukhri was sunk by a Pakistani submarine and Jain, who was on board, lost his life.

Kapoor: Unfortunately

Paulraj: Yes ,It was after Kukhri's loss that I was pulled in.

Kapoor: Mm, right. So in 1969, you were nominated to attend the IIT-Delhi for M.E.. program

Paulraj: I was technically ineligible for admission to a M.E. program since I did not have a B.E. degree. But the Navy recognized that my academic bent and knew about the advanced books I was consuming. So they figured that could use me to break the B.E. barrier at IITs for ex-NDA officers. So, after a few months of fleet service post my training I was, to my surprise, nominated to attend an M.E. selection interview in Delhi. During the interview, I must have impressed an IIT Delhi Professor on the panel (Professor. Indiresan). Indiresan was convinced that I should be admitted into the M.E. program despite my missing degree and arranged for a waiver from the IIT Delhi Senate. That act by Indiresan set the precedent for ex-NDA officers in IITs and thousands have benefitted.

Kapoor: Professor Indiresan, by the way was also my professor because I also went to IIT Delhi, was even more impressed with your grasp of advanced subjects after you joined the IIT and suggested that you transfer to a PhD program. He again got a waiver from the IIT senate and then wrote to the Naval Headquarters to allow you to transfer to a PhD program.

Paulraj: But Indiresan's first letter was not well received and Vice Admiral Krishnan, Vice Chief of Naval Staff gave a flat no, noting on the file that the Navy does need scientists. But Indiresan was not easily deterred and more persuasive letters to the Navy followed till it relented and agreed for my transfer to a

PhD program, but with the condition that I returned to the Navy in two years, the duration of the M.E. program.

Kapoor: Right, right. So you started work in the filtering theory in your PhD work.

Paulraj: Not at first, Indiresan, who I was working with as my supervisor, had a practical bent, and suggested designing a pulse compression receiver for radars. as my thesis topic. I had some reluctance on this as my inclination was for theoretical work. My luck turned when Professor Thomas Kailath from Stanford University came by for some inspiring lectures in filtering theory and that led me to shift to non-linear filtering as the research area. This work needed stochastic calculus which I managed to read up on. It. My thesis unified much of non-linear filtering theory and made a few waves. I returned to the Navy as planned in July 1971. I reconnected with Kailath when he accepted to be the external examiner for my thesis in June 1973. I think he was duly impressed with it and invited me to visit him and give a set of lectures on my work at Stanford University.

Kapoor: Right. So you were exposed to both the theoretical side from Professor Kailath and the practical side from <laughs> Professor Indiresan.

Paulraj: Right. They were different type of influences and very powerful.

Kapoor: Right. In 1971, you returned to the Navy who planned to move you to the Navy's electrical school INS Valsura. in Jamnagar

Paulraj: Right. I received posting orders to Valsura after my tenure at IIT-Delhi ended, That was not good news since it would've taken me away from IIT Delhi with its library facilities and typesetting staff to prepare my PhD thesis. I petitioned the Navy and they thankfully let me stay on in Delhi for one more year. So I was posted to the Naval headquarters on a staff job. My hope was to wind up the thesis by 1972 and then move to INS Valsura. But in a few months, we had this war with Pakistan and everything changed

Kapoor: Right.

Paulraj: Which then took my career in off in a very new direction.

Kapoor: Right. As you were saying that, the name of the frigate was INS Khukri.

Paulraj: Yes

Kapoor: Kukhri was sunk through submarine action. Clearly the sonar (British origin Sonar 170B) on INS Khukri had failed to detect the Pakistani submarine

Paulraj: That's correct.

Kapoor: The morning after Kukhri's loss, you were flown to Bombay accompanying Commodore Chatterjee, Director of Elect. Eng. at Naval Headquarters. He asked you what I knew about sonars,

Paulraj: Right, arriving in Bombay I learnt that a unit developed by BARC and accompanied by Lieutenant Jain was on Khukri when it was lost, and he along with 150 others had lost their lives. Chatterjee suggested that I replace Jain on the BARC work The war was still on. At that time. I visited BARC to understand the core ideas behind their system and quickly concluded that BARC approach had a key shortcoming. I felt that there are better approaches to improve Sonar 170B performance; So I explained all this to Chatterjee and suggested that he send me back to IIT-Delhi, a place I was very familiar with, to develop technology for Sonar 170B. The sonar project had of course nothing to do with my PhD work. The Navy agreed and I happily returned to IIT Delhi to work on this exciting opportunity as the project lead.

Kapoor: Right. But it also helped you to finish--

Paulraj: Yes of course, it also helped me finish up <laughs> my PhD thesis.

Kapoor: Right, very good. So you worked, as you said, on the sonar improvement project at IIT-Delhi, under Professor Indiresan. And you had a prototype by March 1972 that you flew down to Bombay for trials on INS Kuthar (a sister ship to Kukhri) and apparently, the initial trials had some problems. And you went back in June after some improvements, and this time the trials went well.

Paulraj: Yes it was quite amazing that we could improve the range performance so dramatically. More trials followed and confirmed the range and detection performance gains from improved waveforms and the receiver technology we had developed. The Navy, after extensive acceptance trials, approved the new equipment for fleet use and place bulk orders. The IIT Delhi team then readied the production drawings and test plans etc.

Kapoor: And the production was given to Bharat Dynamics Ltd. (BDL) Hyderabad?

Paulraj: That's correct.

Kapoor: In December 1973

Paulraj: We handed over the manufacturing documentation to BDL in end 1973. BDL was actually a missile production outfit, but had unused production capacity, so <laughs> the project was welcomed by them . BDL eventually built several units, which were then installed in all Naval ships with Sonar 170B.

Kapoor: Right. So could you briefly describe the technology in the Sonar 170B project

Paulraj: 170B was a British-sonar using a search-light approach, i.e., you had a single narrow sonar beam that was scanned step by step in azimuth much like in a search light. At each step you would transmit a pulse and wait for echoes to arrive for a set duration, and then rotate the beam by one beam width and then repeat. This rotational scanning continued around 360 till a possible submarine echo was detected at which time the sonar moved to a tracking mode. Because the velocity of sound in sea water is around 4800 feet / sec, each step on search will need about 2 seconds for 5000 feet range setting. If we assume a beam width of 6 degrees, it will take 2 minutes to do one 360-degree search.

Kapoor: Right. So the difference with the BARC approach versus the IIT approach was really highlighted in this.

Paulraj: The BARC approach was to do multiple transmit – receive (dwells) at each step and then electronically integrate the overlapped receiver responses. The detectability of a weak echo weak echo can improve through a process known as incoherent integration where the consistency of the echo versus the randomness of noise and reverberations is exploited, For example, under ideal conditions, If we use a dwell of 10 pulses, we get about 7 dB in gain in signal to noise ratio. The problem with BARC's approach is that a 360-degree scan time now increases to 20 minutes for a dwell of 10. This slows the search dramatically allowing the submarine to approach undetected. A fatal problem. In the IITD approach we kept the dwell time as one, but used new waveforms, improved receiver signal processing and Doppler compensation to improve signal detectability by 12 to 14 dB without slowing the search rate.

Kapoor: Right. So this project was perhaps the first in India where advanced signal processing and use of integrated circuits were used in a successful design

Paulraj: Yes I believe so. Phase lock loops, digital frequency synthesis, chirp compression and others

Kapoor: About this time you received an invite for a fellowship at Loughborough University, UK to work on a array signal processing research project. And so that was good--

Paulraj: Yes, Professor JWR Griffiths from Loughborough University had visited IIT-Delhi and invited me to spend some time at Loughborough as a research fellow.. The Navy was initially reluctant but later agreed. Loughborough stay was useful in many ways. Griffiths had a research project on adaptive array signal processing. I had some wonderful colleagues like Prof. John Hudson and learnt about this field of array processing, something that I would come back to very often in later years.

Kapoor: Right. So it was interesting; I read a comment that, while you were there, you had fun designing a minicomputer.

Paulraj: Right.

Kapoor: Can you tell me a little bit about that?

Paulraj: It was 1974, and I think the Intel 8080 or 8008 microprocessor was available as a bad chip. We were using some mini mainframe computers for signal processing simulation work at the university, but I wanted to try and put something together myself. So I managed to find the funds to build a small microcomputer and wrote an assembler, a tiny operating system, utilities and was trying to write a basic interpreter but did not finish that last one. It was my way of learning computing - by building one.

Kapoor: Of course.

Paulraj: It was 1974.

Kapoor: Very good. Of course, then you returned to India in 1975, but before I go forward, obviously, your family must have been very proud of you for all the achievements even until then. And I did not read and I don't know when you got married, for example. Feel free to tell us about--

Paulraj: Right. In India, as you well know <laughs>, in those days arranged marriages were the norm, I was about 27 years, working on the 170B project at IIT Delhi. I think my parents felt it was time and were looking around for a bride and I was with that. One day, they announced that they found someone suitable. That is a code word for similar social status, same religion and so on. I was flying around India, on this 170B project and I halted in Hyderabad for a half a day to meet this young woman, and my mother had also come by, and clearly both the potential partners agreed, and so a year later there was a wedding. It was held in Secunderabad with lots of family as is usual in India.

Kapoor: I see. When was this roughly?

Paulraj: 1973 February. And by then I just was finishing up the 170 B sonar project-

Kapoor: I see.

Paulraj: I also submitted my rather mathematical thesis, which my wife helped to proof read <laughs>.

Kapoor: Oh, okay.

Paulraj: The thesis had complex math expressions and typing it was a big effort. I submitted my thesis, in June 1973, got the sonar manufacturing launched at BDL and then went to Loughborough in early 1974.

Kapoor: Okay. Did she go with you?

Paulraj: She came with me, yes.

Kapoor: Okay. So you returned to India in 1975, and then you installed a sonar mod kit, as it's called, which you developed in England apparently. Is that true?

Paulraj: Oh no, the Sonar 170B improvement unit designed at IIT Delhi. was also known as a Mod Kit. My work in England was just theoretical signal processing. research. Yes, I did build that small computer as a hobby.

Kapoor: But I read somewhere that, while you were in England, you also had done the mod kit in England.

Paulraj: Not so. My Loughborough research work had nothing to do with the earlier 170B project or the later APSOH project.

Kapoor: I see.

Paulraj:, The Indian Navy, because we had lost Kukhri , were looking for a panoramic sonar, because the searchlight sonars are handicapped by the slow search process. Panoramic sonars look all round simultaneously. The Navy had placed orders for first generation panoramic sonars with firms in the UK and France and whilst I was at Loughborough, I was instructed to visit these firms.

Kapoor: Right.

Paulraj: I visited Graseby Systems in UK and Thomson CSF in France. They had good teams, but I could see that that the 17OB work done in India had used far more advanced ideas than what I saw there.

Kapoor: I see.

Paulraj: When I returned to India, I realized that the Navy had upped their sights to a second-generation panoramic sonars and were scouting for them in the US or Russia. I felt we could build these sonars in India and met with several key people. I was now due for afloat service, but the Navy, in their wisdom, decided to waive that requirement and send me to Naval Physical and Oceanographic Laboratory NPOL in Cochin. NPOL had not developed any sonars but had the charter to do so,

Kapoor: Before you went there, you installed the Sonar 170B mod kit on the INS Talwar.

Paulraj: That's right. The equipment was installed in several ships, but I was involved in first one or two installations.

Kapoor: I see. Okay. So you move to NPOL in Cochin to work on the panoramic sonar.

Paulraj: Not quite. NPOL was under Defense R&D Organization and not a part of the Navy. When I arrived at NPOL, there was already a tiny panoramic sonar project running. But my first job was officer in charge of the NPOL library, perhaps because I was, apart for the Lab director, the only other PhD at the lab. I was excluded from the sonar project, even though I had led the first and only successful sonar work in India.

Kapoor : And I think there was an interesting episode when you moved to NPOL. I read that initially there was not a lot of excitement involving you because work was already going on, and then there was a computer that arrived damaged, and you fixed it, and Dr Srinivasan ..

Paulraj: Right. NPOL was suspicious of an outsider like me. Very understandable. Despite my credentials, I was a service person and not quite a sceientist..

Kapoor: Right.

Paulraj: So they didn't know what to do with me. I was thinking of asking the Navy for another posting, But then had a stroke of luck. NPOL had ordered a PDP-16 computer-- which arrived after some damage during shipment and would not boot up. The local agents in Bombay could not fix it and suggested we ship it back to the US for repairs. Thanks to my Loughborough computer experience, I knew enough to rewrite some the boot code and bring up the machine on a new boot device. This work, strangely enough, did the trick. I was invited to sit in on the sonar project meetings. Everyone on the team soon realized that I should be leading the project and in a couple months I was put in charge, I completely revamped the project to meet th Navy's 2 or 2.5 generation requirements. The budget was increased by over 20 times which also meant the Navy had fund it out of its main equipment budget. Essentially the Navy was placing an order for sonar not yet designed. That meant that if I did not deliver, the warship under construction will have no sonar. I remember the Naval brass telling me that I was playing with fire. All this took some persuasion in Delhi. For the first-time Indian military was committing to a major indigenous technology purchase foregoing imported technology. Vice Admiral Pereira, the Vice Naval Chief, decided to bet on me and pushed for cabinet approval needed for this and that came in Feb 1977. The project was called APSOH (Advanced Panoramic Sonar Hull Mounted). I was the Project Head. It was at that time the biggest military technology project in India.

Kapoor: Right. So in 1977 work really started on APSOH, when did the trials start?

Paulraj: APSOH was a large all digital sonar with 20 plus subsystems and very advanced technology. I think it remains classified as secret even today, and so I am unable to elaborate more. Sea trials of individual subsystems started in 1980. Most of the functions were software driven and so we could learn and adapt the design as the trials progressed. The project team consisted of about 200 engineers in design team at NPOL Cochin, production team at Bharat Electronics (BEL) in Bangalore, Installation Team at Mazagaon Shipyard in Bombay, Inspection Team in Bangalore and later a Naval Evaluation Team in Delhi.

Kapoor: Right.

Paulraj: A fully- engineered, system was produced by BEL for a multi-year sea trials by mid-1982 and then installed on INS Himgiri, a frontline frigate. Himgiri's existing sonar was removed and APSOH installed instead.

Kapoor: Right.

Paulraj: APSOH was a big system with 20 water cooled cabinets, a chilling plant, a dedicated power generator, a large cylindrical hull mounted transducer and three operator consoles. It occupied multiple compartments. It took six months to install APSOH at a dockyard in Bombay. The yearlong trials started in end 1982

Kapoor: Right.

Paulraj: And from first day at sea the trials was a dramatic success. I would never have expected that.

Kapoor: Right.

Paulraj: Certainly, better than any sonar that the Indian Navy had seen in the world, so it is clearly a winner. We did have a problem with frequent failures of Power Amp modules in rough seas – that was easily fixable.

Kapoor: Right. And I think you also played a key role-- there were a lot of issues between NPOL and Bharat Electronics.

Paulraj: Right. Yes, I was the Project Head (i.e. Project Director).and kind of Chief Scientist. There was some acrimony between NPOL and BEL <laughs> NPOL were the design agency, and BEL the manufacturing agency. There were errors in transfer of design drawings from NPOL and BEL also made mistakes on their side. One source of the problem was poor communications. The NPOL team had only one office phone (on my desk) to contact BEL and other agencies and these trunk calls often failed. No fax service and no email of course. Poor communications was a real issue. I did not even have a home phone till end 1982, - I was too junior. Another problem was that I ran everything - from concepts, to system design to implementation issues, etc. That level of intellectual control made others feel powerless.

Kapoor: Right, so in retrospect, I read you said, "I'm always amazed as to how such an inexperienced team with such few resources pulled off this major project in such a short period. APSOH was an impossible dream that came true for many of us." Those are your words.

Paulraj: I agree, and in fact, during the APSOH project, I would run into sonar companies - Raytheon in the US, Thompson in France and the Russians, and they would all say, something like "Paul, this is impossible. You don't have the team to build such an advanced system." Sure the team at NPOL was inexperienced, but , I had the advantage of the doing 170B project and taking it all the way to fleet service. And the engineering / manufactur9ing team in Bharat Electronics knew how to build robust Naval systems, everything worked out in the end.

Kapoor: So in June 1983, as the APSOH trials were concluding, your scientific boss, Dr. Arunachalam, the scientific adviser to the Defense Minister, suggested you take a sabbatical abroad, your sonar days that started with Kukhri's sinking in 1971 seemed to be ending or pausing…

Paulraj: Yes, I assumed I will get back to sonars after my sabbatical, But after I joined Stanford, Dr. Arunachalam came visiting to Silicon Valley and I remember at a dinner-- maybe it was with Lockheed Martin, he announced that my sonar days are over and I should do something else in the future <laughs>."

Kapoor: <laughs> I see. That's good. To go back to your coming to Stanford, you contacted Professor Kailath.in May 1983 when Arunachalam suggested a sabbatical?

Paulraj: At first, when Arunachalam suggested a sabbatical, I thought of Loughborough University, where I had spent a year in 1974.

Kapoor: I see.

Paulraj: But Arunchalam suggested that I go to Stanford instead and asked if I knew anybody there. I did - Prof. Kailath, we had met once during my PhD work ten years earlier. So I wrote to him, though with much hesitation, as I felt Stanford was above my league. I never fully understood why Arunachalam was so keen about Stanford. I think he knew about Stanford's reputation much better than I did. He did me a huge favor.

Kapoor: Okay. So you contacted Kailath, and he eventually asked you to join Stanford as a visiting faculty.

Paulraj: Right.

Kapoor: In 1983.

Paulraj: Yes October 1983. Initially, Kailath declined <laughs>

Kapoor: I see.

Paulraj: He wrote back saying, something like - "You're a practical engineer, and my group here is very theoretical so you would not fit in," He must have remembered my very theoretical PhD work, but that was a dozen years earlier. I mentioned Kailath's response to Arunachalam, who suggested I write back and try and be more persuasive. So I did write, maybe once or twice, and Kailath finally relented. I was supported fully by the Indian Govt.

Kapoor: Okay. So you came to Stanford, and your work was, as expected purely theoretical and mostly applied mathematics.

Paulraj: When I landed in Stanford, and I encountered a new area of mathematics called linear algebra. I had almost no exposure to Math in the Navy and my PhD thesis used stochastic calculus and measure theory. Linear algebra was new.

Kapoor: Right.

Paulraj: Linear Algebra was essential for my work at Stanford and I picked it up thanks to good books available. Kailath's group was now looking at directions-of-arrival (DOA) estimation using antenna arrays. He had funding from DARPA, I believe.

Kapoor: Right. When I was doing Kailath's interview, I realized that when I read about the work on multiple signals DOA problem, I think some of that work started at MIT under Shannon, and Kailath's thesis involved that. He was given that as a task.

Paulraj: Yes, Kailath was looking at communication in a multi-path propagation channel for his thesis at MIT, and the DOA problem also had to deal with multi-path issues

Kapoor: Right, So you worked on multiple signals DOA problem which had a long history of results always using a "spectrum" approach. Then you proposed a totally new method called ESPRIT. **-** Estimation of Signal Parameters via Rotational Invariance Technique

Paulraj: Correct

Kapoor: Which caused a mini-revolution, so maybe you could talk a little bit about that.

Paulraj: It was interesting the way I came to inventing ESPRIT, and it goes back to my APSOH sonar. In APSOH, one function was DOA estimation of vessels using their emitted noise (Passive sonar). And it turned out the best way to do so would be to scan a beam and look for the peak power response. But, during APSOH design phase, I had explored an alternate method which you scan a null beam and look for the minimum power response. In this latter method, you scan a sharp null beam, rather than a shallow full beam. Null scanning might appear to be a better approach than beam scanning, but theory showed otherwise. APSOH used beam scanning But the idea of null scanning was in my mind, when I worked on the multiple signals DOA problem at Stanford. Simple null steering does not work anymore here since even if one of the signals was nulled, the other signals come through and you don't get the expected minimum.

Kapoor: Right.

Paulraj: I was looking for some other mathematical object which would go to zero or dip, when one of the signals was nulled, and that led to the ESPRIT algorithm. It launched a whole new paradigm, now called, subspace fitting. This is now a very useful tool today

Kapoor: Mm-hmm, right. And apparently, many papers were published. I read thousand--

Paulraj: Yeah, well over a thousand papers, and over 100 doctoral dissertations.

Kapoor: Wow. So the applications go far beyond the array signal processing to spectral estimation and to system identification.

Paulraj: Yes and now even in biology, machine learning and others. It was such a neat and a fresh idea, people would often ask me where did it come from <laughs>? ESPRIT became a revolution with entire workshops and mini-conferences around it.

Kapoor: <laughs>

Paulraj: It was so different. There was a long history of solving the DOA problem and they all took a different approach-- spectrum method

Kapoor: Right.

Paulraj: And ESPRIT was a completely new approach.

Kapoor: Right, right, so it's the physical rather than the mathematical insight--

Paulraj: My APSOH experience certainly underpinned the ESPRIT idea, but I also needed the mathematics I picked up at Stanford.

Kapoor: Right, generalization of the sonar work, as you mentioned. Then of course, your Stanford time ended and, you returned to India in 1986 and served as the founding director of three major labs: The Centre for Artificial Intelligence and Robotics, Center for Development of Advanced Computing, and Central Research Labs of Bharat Electronics. So how did that come about?

Paulraj: I returned in ‘86, and Dr. Arunachalam plans for me was to take over as Director of a large electronic warfare lab (DLRL), with 1000s of scientists. And I was 42 and the heavy administrative load as Director was not appealing. I wanted to do R&D rather than administration. I spoke to the Naval Chief about my concerns and suggested I set up a new lab on Artificial Intelligence. He managed to convince Arunchalam and I was assigned to found a new lab titled Center for Artificial Intelligence and Robotics (CAIR) under DRDO.. I had run into Professor Raj Reddy at Carnegie Mellon and he provided moral support. I knew that AI was still an infant technology, and real products for defense may take years if not decades. But there were a class of systems called Command Post Systems needed urgently by the Armed Forces and I focused the new lab on that mission, with the hope AI can play some role in these systems. But again, fate intervened. India had initiated an ambitious program in 1983 to build a fighter jet called a Light Combat Aircraft LCA, and Arunachalam felt that I should lead or co-lead LCA program because of my outsize success in APSOH.

Kapoor: I see.

Paulraj: But I wanted time to get prepared. Aeronautics and fighter jets was new for me and I started by getting exposed to combat jets in the Indian Air Force, did some flying in trainee versions, understand Air Force culture and how combat jets were acquired, maintained and operated. I also visited aircraft factories that manufactured jet fighters under technology license agreements. I met with Air Force Chief to see how he viewed the LCA program. This was around 1987 and Arunachalam kept telling me that he wanted the LCA to fly by 1989 or 90 at the latest. Certainly very ambitious, in the best of circumstances But my own experience with egregious bureaucratic bottle necks at CAIR convinced me that the LCA program, or at least the part I would run, needed a different management structure, and must be set free from very unreasonable constraints of a Govt. controlled lab. Arunachalam backed me on this and we planned a private-public partnership with Tata Sons. This would done via a Society as a legal framework and I got the paperwork with Tata’s done and wrote the proposal for approval by the Union Cabinet. This was going to be a large effort with hundreds if not thousands of engineers. As is usual in India, I had to be in Delhi every week to “push” the file as it threaded its ways across various ministries before it reached the Union Cabinet. I visited Delhi for many months and it became slowly clear that Arunchalam had second thoughts on the proposed, no doubt rather unusual, laboratory structure. The Naval Chief, who saw my rising frustration than decided that I should to get back to supporting Naval rather than Air Force projects. and terminated my deputation to Arunchalam’s organization. I was soon assigned to Bharat Electronics, as their Chief Scientist. BEL manufactured a lot Naval equipment and the Navy thought I would perhaps be more useful there.

Kapoor: I see.

Paulraj: BEL was India's largest for military electronics company and manufactured military communications, radars, sonars and components. They were about 20,000 string with factories all over India. BEL, you recall, also manufactured the APSOH sonar. BEL's largely relied on licensed technology from abroad or design transfer from DRDO (like APOSH) and sometimes evolved their own designs from earlier technology transfers

Kapoor: Mm-hmm.

Paulraj: My job at BEL was to create an internal source of technology and reduce dependence on imports. I started two Central Research Labs for BEL – Bangalore and Ghaziabad. The then Managing Director of BEL, Capt. Prabhala was enthusiastic but the mainstream of BEL, not surprisingly, unfortunately saw CRL as a threat. And as I was settling down at BEL, Mr. Sam Pitroda- reached out to me.

Kapoor: Yes, I've met him.

Paulraj: Mr. Pitroda was trying to put a high-speed computing effort called C-DAC. This was around 1988, India was trying to buy the Cray Supercomputer from the United States. And the US was willing to sell us one, but they did not want it to be used for India's nuclear weapons program and demanded day to day oversight of Cray's use, Obviously the Indian government decided not to buy the Cary, And Mr. Pitroda, a hugely powerful figure those days, opted a build a machine in India and roped me into the project. I was now simultaneously running a part of C-DAC (Systems Software) for Mr. Pitroda and the CRL for BEL It was clear that India had no way to build a Cray, we did not have the high speed semiconductor technology to start, leave alone architectural and systems software experience.

Kapoor: Right.

Paulraj: Cary was too long a bridge to cross.

Kapoor: Yes, in fact, I was going to ask you; Bharat Electronics had a manufacturing plant for semiconductors?

Paulraj: BEL could only do low complexity devices (like watch chips) and BEL's semiconductor node technology was 3-4 generations behind what was needed for a Cray,

Kapoor: Right.

Paulraj: So the option we took was a message passing parallel computer using the best microprocessors available to India. We knew, thanks to Amdahl's law, that this machine would not scale well on all problems, but for some, it will do a pretty good job. The key then was high speed inter-node communication and good software and tools. C-DAC over the years went on to build large parallel machines, but it never reached an international reputation. I stepped off the C-DAC project in a couple of years due to my growing responsibilities at BEL.

Kapoor: Okay, thank you. So then what made you come back to Stanford?

Paulraj: Okay, <laughs> that's a good question. The root cause of my move back was my experience with the LCA program, a super important national project. In my time with LCA, I saw that inter-personal politics overtaking national interests. With a few exceptions, most people did not seem to be fully invested in these projects In the LCA program, at BEL and even at CDAC, I seemed at odds with the prevailing culture. There was a penchant for importing technology and declaring victory even when the value added was minimal. Clearly Dr. Arunachalam, Mr. Pitroda and Capt. Prabhala and particularly Admiral Pereira were outstanding leaders with a visionary mold, but the overall culture in Indian Govt. R&D was far less progressive., to put things politely. My early success at the age of 35 in APSOH did not help. Also, I missed academic life that I had tasted at Stanford. So I began to consider switching to an academic career, no doubt at the age of 47, was rather late. An obvious option for me was to join as a faculty member one of the IITs. But I did not seriously check out that, assuming without evidence though, that being a naval officer and an Indian PhD. would be roadblocks. Also, I remembered that when I was at Stanford in 1984-86, Kailath had casually asked me if I would like remain at Stanford and be a part of the faculty. It was not an option then, but now looked attractive.

Kapoor: OK

Paulraj: So I wrote to Prof. Kailath in June 1991 about a post-doc position at Stanford. He pointed out that US was going through a recession and funding was tight, but did offer a positon as a research associate as a start and see how things work out. My work in India was not relevant to an US academic career, but the ESPRIT algorithm was well known.

Kapoor: Indiresan would have been one choice to approach if you wanted to join the IITs

Paulraj: That's true. But Indiresan had retired by that time. Certainly, Indiresan would have helped if I asked him. But many people in India, including the then Naval Chief advised me that APSOH was an outlier and the norm in Indian R&D was more difficult and therefore I that should look elsewhere. !991 was a bad time for India with a huge financial crisis and budget cuts.

Kapoor: Right.

Paulraj: And clearly, I think the fact that I had a potential option at Stanford certainly dominated my decision to leave

Kapoor: Right. I remember Professor Indiresan came here, and we had lunch together with our group, and I remember his card had a government designation; he was working for the government, so he had a role advising.

Paulraj: Yes. He was President of the Indian National Academy of Engineering. That might have been it,

Kapoor: Could have been that.

Paulraj: After he retired at the age of 60, I worked through BEL to get him a fellowship or a professorship at IIT Delhi. Someone with his vision had so much to offer.

Kapoor: I see. So when you came to Stanford in 1991, while awaiting a faculty position, you worked on a signal separation experiment for airborne reconnaissance. Was this for the US Air Force?

Paulraj: Yes. Somebody at Stanford had to cover my salary. Kailath had some money to get me started, but I needed a year of salary support to see if my faculty appointment was successful. . There was a well-known math professor called Gene Golub at Stanford, and who had a DARPA program to look at a airborne reconnaissance signal separation problem. This problem had a long history of different algorithms, and apparently, even the best of them had numerical instability issues. Golub welcomed my help in this project. Meanwhile Kailath manage to get a Research Professor billet sanctioned and a search was launched for the position and I applied.

Kapoor: Okay

Paulraj: Back to the DARPA project. The standard approach to work on algorithm research was to use MATLAB based simulations of signals and algorithms I was suspicious of MATLAB generated signals – maybe they did not capture the real world accurately, and decided to build a little prototype to generate real signals. I used cordless phones operating in the same channel as a cheap signal source and small three antennae base station to collect the signals. During these experiments, I found that when the phones were far apart in angle, signal separation worked as expected, but when the phones became close in angle, the algorithm failed, exactly as expected

Kapoor: Right.

Paulraj: But one day it rained, and we pulled that antenna base structure into the foyer of the Durand Building, to avoid the rain, and I was waiting for the rain to stop. However, the experiment was still running with some student helpers walking around with phones, and I noticed that even when the cordless phones were next to each other, the system still capable of separating them. That was unexpected. Very quickly I found the explanation - multi-path propagation, Though an interesting insight it was not relevant to the DRAPA project which had no multi-path propagation in that application

Kapoor: Yes.

Paulraj: But some days later--

Kapoor: You, in fact, were sitting in a barber--

Paulraj: Yes at a Barber shop.

Kapoor: Yes

Paulraj: In Mountain View, mulling about what I had observed. I could separate signals from co-located phones, So. Instead if I have two antennas on the same phone, I would be able to send two data streams in the same frequency channel, and using two or more antennas at the receiver to separate them. That would double the link rate. So back at home, I did some quick calculations and was convinced that if you have M antennas on each side of a radio link (MIMO) you've got M times the capacity without any additional power or other penalty. This was a new idea. But there was a problem – I had noticed that the signal separability was erratic - small changes in phone positions could. damage separability. So the system would have adapt rapidly to when the signals were or were not separable. Today MIMO in 4G works by adapting to the channel. But then, in 1991, I saw this as a huge problem for mobile applications and tried to find an application to make MIMO work reliably – which led to highlighting an application to broadcast problem with roof top antennas.

Kapoor: Right. So the patent you mentioned was the DTDR--

Paulraj: That's right.

Kapoor: Distributed transmit-directional receive.

Paulraj: So that was an application where MIMO worked all the time.

Kapoor: Right.

Paulraj: MIMO is now being used in television broadcast, as outlined in DTDR,, but its earliest applications came in mobile systems and the variability of separability is handled easily by rapid adaptation, at least for slow moving pedestrians. We still cannot do MIMO at vehicular speeds, as I had feared in 1992. However, now 95% of broadband traffic is fixed or pedestrian, so I was too pessimistic then.

Kapoor: Right. So the patent was granted in Sep. 1994. and the idea is known as spatial multiplexing.

Paulraj: Yes

Kapoor: And it boosts the spectral efficiency by creating parallel spatial data streams within the same frequency channels. Again, it was the visual thinking, just like ESPRIT

Paulraj: That's correct. It was visual thinking, and it was also inspired by a physical experiment. It wasn't something that came from sitting in front of a whiteboard and thinking about a problem

Kapoor: Right, right, so it's very interesting that ESPRIT and then MIMO--

Paulraj: Both came from the physical world.

Kapoor: You were appointed a professor of research in '93, and you built a large research group around MIMO, and you graduated more than 50 doctoral and post-docs.

Paulraj: Yes

Kapoor: The spatial multiplexing techniques make the receivers very complex, and therefore they are typically combined with orthogonal frequency-division multiplexing, OFDM. Can you say more

Paulraj: Yes, MIMO can be used with any modulation or multiple access system. In first generation, it was FM modulation and FDMA, And the second generation, we adopted digital single carrier modulation and TDMA. A third generation used spread spectrum modulation and CDMA. So MIMO could work with all of them in principle, but it turned out that there was one particular modulation known as OFDM and multiple access method called OFDMA, which suited MIMO well by making MIMO decoding simpler.More over OFDM also had other advantages for wideband systems.

Kapoor: Right.

Paulraj: So MIMO-OFDMA was the right combination, and this marriage didn't happen at Stanford but when I started Iospan. In 1998

Kapoor: Iospan.

Paulraj: At that time CDMA / spread spectrum was by far the ruling cellular technique and MIMO-OFDMA was a bit of a heresy.

Kapoor: Right.

Paulraj: >. So it took some effort to-- and certainly with Qualcomm to move them away from CDMA. I think it is only around 2006 that they finally switched.

Kapoor: Yes, I understand that there was a very strong skepticism

Paulraj: In fact, I met with Qualcomm leadership, around 2000 and 2001 but it proved a hard sell. Qualcomm also had invested a lot in CDNMA and needed to recoup some of that.

Kapoor: Right, And especially the practical feasibility, from a concept it was okay, but as a practical solution--

Paulraj: In fact, CDMA has some nice advantages like interference diversity and it worked well for voice networks. With MIMO-OFDMA, interference diversity was harder, but. MIMO-OFDMA had many other huge advantages. It is now the gold standard for all modern wireless systems

Kapoor: Right.

Paulraj: Wi-Fi uses it; 4G uses it; 5G will use it.

Kapoor: Right. And it's got the scalability

Paulraj: Yes. You can keep scaling up on antennas; with the throughput going up proportionally, and with OFDM, bandwidth also scales up well too.

Kapoor: So let's go back to Iospan. So you founded Iospan, and that became very successful, and then later on, you sold it to Intel in 2003. And that basically proved MIMO's feasibility

Paulraj: ,Yes. In Iospan, the focus was a cellular system, but for fixed and nomadic application not full mobility with hand overs. Iospan realized quite correctly that a mobile system needed a global standard to build a market. A small startup company had no chance. to do so. A fixed access system could find a market without technology standardization. By 2001, we had a nice demonstration set up in Santa Clara.. We had our first trials customer in Dubai. But by 2002, it was clear that the future of MIMO-OFDMA was in broadband mobile systems, and that was not a market we could pursue with limited funds. At that time Intel was looking mobile internet technology so they acquired the company and dubbed it WiMAX. I remained an advisor for a year. Intel invested in huge effort to standardize and proliferate WiMAX and also build WiMAX semiconductors. I got to know Intel execs like Sean Maloney well.

Kapoor: So going back a little bit, how did your family fare? Because you were going back and forth between countries.

Paulraj: Right. My children were born in India, attended kindergarten here, then went back to primary and middle school in India, back here again for high school. My younger daughter also went back to college to India, so there were many moves. I think it's was tough on them, but in the Indian armed forces, children moved every 2-3 years, thanks to transfers, so not that different.

Kapoor: Right.

Paulraj: But I had only two permanent jobs during all those 45 years – Indian Navy and Stanford. So there always was financial security. Though salaries were modest most of the time.

Kapoor: There was always a continuity.

Paulraj: Yes

Kapoor: Right, And then in 2004, you cofounded Beceem Communication. So this is more in the semiconductor domain.

Paulraj: Right. I had just finished up with Iospan and was back at Stanford. My new project was a text book on MIMO. Aided by two of my then PhD students Rohit Nabar and Dhananjay Gore. Then Mr. Babu Mandava came to see me in my office with a proposition that I join him in a wireless semiconductor start up. Babu was a brilliant person, though I did not know it then. He had just finished up a DSL company. I was initially hesitant and kept putting him off. Soon Babu's colleague Shahin Hedayat also joined the team. Finally, a venture capitalist who knew Babu and Shahin finally persuaded me. That's how Beceem got started.

Kapoor: I see. I guess you provided the wireless technology

Paulraj: Yes, I brought the wireless systems piece, and recruited the systems team including some of my former students. Babu brought the chip team. Shahin was CEO. Soon Intel's program on WiMAX began to grow and we knew that Beceem could pursue that market opportunity, though it meant competing head on with Intel.

Kapoor: Okay.

Paulraj: So it was a good combination of both skill sets

Kapoor: Right. And at one time, you had 65 percent of the market share.

Paulraj: Yes, we were clearly the leader; around 65 percent market share. WiMAX was not a big market, but we reached $ 100-million annual revenue. WiMAX had a good chance of being the 4G technology, but IEEE standards body that developed the standard had some blind spots. The 3GPP standards group who were at the time evolving 3G WCDMA, saw a threat in WiMAX and realized that MIMO-OFDMA was the way to deliver wireless broadband.

Kapoor: Right.

Paulraj: So they jumped onto it--

Kapoor: Nice.

Paulraj: And created the standard called LTE.

Kapoor: Right.

Paulraj: And so that's basically MIMO-OFDMA of WiMAX rebranded as LTE.

Kapoor: Right, right.

Paulraj: When 3GPP defined LTE from 2008 onwards they made sure it was fully aligned and backward compatible with cellular ecosystem like band plans and inter-RAT handover. WiMAX, because it had come from the IEEE standards side, didn't have that seamlessness of LTE. So WiMAX's appeal began to decline. The Chinese were also opposed to WiMAX. earlier in 2003 thinking it threatened their own 2G technology known as TD-SCDMA. LTE became dominant, MIMO-OFDMA based 4G technology and Beceem also began shifting product focus to LTE.

Kapoor: So the 3GPP standards group developed LTE

Paulraj: Yes, though 3GPP standard group was formed to promote 3G CDMA standards, they have stayed with that original name. though they moved to 4G and now to 5G.

Kapoor: Right. So with all your achievements, your Stanford colleague and Marconi fellow professor, John Cioffi, inventor of the DSL technology, calls your technical capability almost unparalleled in the world. What impressed him most is how you endured the tremendous pressure, turmoil and stress of people saying your ideas weren't going to work, and you persevered until you found success. People such as you are pretty rare. This is coming from an esteemed colleague and peer, so it's very high praise indeed. You have won the two top telecom recognitions, the IEEE Alexander Graham Bell medal, which emphasizes theoretical contribution, and the Marconi Prize, breakthrough ideas that products benefiting billions of people, so again, this is amazing. So you have also mentored many people at Stanford. Can you say a few words about your professional life?

Paulraj: Sure

Kapoor: Of course, also you were honored with your book on MIMO on your 60th birthday, with a preface by Professor Kailath.

Paulraj: Well, I think the great pleasure of being at Stanford was working with students, and Stanford attracts very good students from around the world, and I too had exceptional students. And your relationship with students PhD and Post-Doc is lifelong -- not as a research collaboration, but you're there to help with their promotions, awards and their career. And when I travel, I'm going to Europe on Monday, one runs into the students everywhere <laughs>. So, it's been an extended family for me. I would put the student relationships, as the best experience I had at Stanford. Occasionally, I would pick up a student from another research group who was dropping out of the PhD program, and take them on, and like the story in "My Fair Lady," sort of make them into a star <laughs>. I've done that twice, working closely with the student to get their self-confidence back and a PhD degree from Stanford. And of course, Prof Kailath was a great mentor and friend. I would not have been at Stanford without his help. Many other senior colleagues like Prof Tom Cover and others, understood my unusual background and handicaps and made me feel at home.

Kapoor: Very nice. So let's talk a little bit about the future. The potential for MIMO to multiply capacity in wireless spectrum seems as limitless. I think you mentioned millimeter band frequencies can soon enable much larger number of MIMO antennas and corresponding boost in wireless capacity. Can you spend a little bit of time on that?

Paulraj: The way MIMO works is that more the number of antennas, more the capacity or data rate. Every antenna sort of gives you one more use of the same bandwidth or channel. In the current LTE, we use frequencies as low as 700 megahertz, and those antennas at the base stations are 2 meters high and about 20 centimeters wide, huge. You can't put many of them on a base station, so the MIMO effect is limited. But in the millimetric band like 28 or 60 Gigahertz, the antennas become really small; only a few millimeters across, and so in a panel of 15 by 15 centimeters, you can have a few hundred antennas, boosting the MIMO potential

Kapoor: Right.

Paulraj: Spectrum is also scarce in the lower bands, because everybody wants to use it for good reasons All current mobile communications is crowded below three Gigahertz. But millimetric band extends to 100 Gigahertz and beyond, so obviously, there is lots of new spectrum there. But millimetric band comes with some challenges. One is reduced range, not so much that the radio energy is absorbed by the atmosphere, but rather from the smaller antenna size used at millimetric frequencies. One way to improve range is to use lots of these small antennas and then combine their energy via beamforming. In millimetric band, beamforming and MIMO work together. MIMO with hundreds of antennas – or commonly known as Massive MIMO does have other challenges - for example, the Analog to Digital (and Digital to Analog) conversion is power hungry at these large bandwidths and with large number of antennas used, it becomes expensive. There are thousands of researchers and engineers working to solve these problems and Massive MIMO will happen soon. The higher bandwidth and higher MIMO leverage together combine to give a 1,000 X higher throughput in 5G where the new applications will demand that.

Kapoor: Is mutual interference between radios an issue?

Paulraj: Interference is always an issue and the modern radio technology like 4G uses several methods to avoid or mitigate interference. This remains an area of active research.

Kapoor: Thank you. That was very nice. So I have only mentioned a few awards and recognitions; of course, you have had so many more awards, and you're a member of so many academies and so on, it is visible on your <laughs> website, and so I will not repeat it.

Paulraj: No need

Kapoor: But I really want to acknowledge that, that you're very well-recognized and deservedly so. You and your wife have been frequent visitors to India to emphasize a need for India, for example, to build its own telecom technology industry. What are your thoughts about India?

Paulraj: I worked for many years in India and still retain my connections somewhat. I have focused on Indian High Tech industry policy. India has many strengths. We have a good auto industry and pharma manufacturing base. A huge IT services industry. India has also done well in some areas of high technology, like the space program, where we built launch vehicles and satellites, a lot of it done indigenously,

Kapoor: These are some amazing results.

Paulraj: And. The space program was also done at very low cost

Kapoor: Yes.

Paulraj: Apart from the space program, other high tech achievements are in the military sector. APSOH sonar which I led nearly 40 years ago, was an early one, the missile program, in particular Brahmos missile in collaboration with the Russia, the LCA is finally flying and will see a limited deployment by the Airforce, and a few others. In both space and military programs, one department of the Government was the manufacturer cum seller and another department was the buyer. This meant limited competition. Large subsystems are often imported and there is little pricing pressure. However, in the mass market arena, where hundreds of millions of people use the technology, from laptops to cell phones from civilian jets to precision instruments, India tends to import them with little or no value added internally. These technologies come from highly competitive global ecosystems. with huge pricing pressures. India is yet to build high technology companies than participate and compete in such global markets Among many issues with such dependence on imports, is affordability. In ICT alone, our annual import bill is around $ 150 billion, and with 5G and smart cities, imports will become much larger. China's story in high technology has been much more impressive. In China, the government is a very active player in technology policy, writes big checks and makes risky bets, even when not all of it succeed. India, is organized differently and China's model will not work. Mass market ICT is best done in the private sector and the Indian Government has yet no effective way to nurture this sector, though different models are still being tried. In recent years, I've been focusing on working with young professors at IITs and getting them to build wireless technology prototypes, to get their feet wet, build confidence and eventually help them start innovative companies. I am confident that India will get there eventually, we just have to recognize our strengths in really good engineers, our problems in our bureaucratic system and try a bit harder. My wife and I, both have family in India, so we're there quite often.

Kapoor: Mm-hmm, thank you. So some comments about your advice to the next generation. With all your experiences as an academic and industry, what would you recommend

Paulraj: Sure. A few words about my about my own experience. I've benefited from mixing theory and practice. I was a practitioner <laughs> for many years in India, save for two years of PhD research at IIT Delhi-. My job: in India was always to build systems- - but coming to Stanford, the focus shifted to theory, again, save a few startups. So I've been fortunate to walk in and out of these two <laughs> parallel corridors I would also add that my influential ideas like ESPRIT and MIMO were inspired by practice. Likewise, when you build things, you really want your theory straight to make sure things work, So a theory - practice career combination is useful, Most academics in universities rarely get an opportunity to work in industry and vice versa. So, one advice for the younger generation is to find ways to mix things up. Another comment I would make is that it is not for mortals to command success, and <laughs> failures are often more common. than success. To survive failures one needs perseverance. I would also add that most things worth doing are also invariably difficult to do, and a capacity for hard work, to persevere and struggle is essential. I wish I had more of those qualities. But I always had the reputation as the hardest working person on the team, of course in my younger days

Kapoor: Thank you very much. Any other comments you'd like to make?

Paulraj: I would just say that we live in interesting times. Many technologies abound and new ones are on the horizon.. Wireless has had a big impact and its future looks even brighter, but I'm fascinated by Artificial Intelligence (AI). I was involved with it many years ago, at CAIR,, and I came back to it recently through a small company. AI has gone through some ups and downs, but we are seeing interesting performance in some domains; There's more to come.

Kapoor: Yes.

Paulraj: And AI could kill jobs. I think that needs careful thinking. People need jobs for more than just to making a living, and how do we build a just society where more and more of the jobs could be taken over by AI? But we are certainly at an interesting juncture of risks and opportunities.

Kapoor: There's a convergence of capabilities happening as well, which can enhance the capabilities of AI in other areas.

Paulraj: And I would say that if you look at how semiconductors and wireless has grown, I doubt one could have predicted their advances or the applications they have enabled. So, AI and other high tech offer great promise. that will likely outstrip our capacity for imagination. But there is also the looming problem of wealth inequality

Kapoor: Yes.

Paulraj: And our society cannot not survive peacefully with this a growing inequality.

Kapoor: Right. And other larger issues of survival of our species.

Paulraj: Right, we have many challenges.

Kapoor: Thank you very much, Professor Paulraj.

Paulraj: Thank you very much. Thank you.

END OF THE INTERVIEW

