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At the heart of 21st Century communication

Arogyaswami J Paulraj's breakthrough ideas are the basis of today's Wi-Fi and 4G systems. His array of breathtaking original ideas in a long and illustrious career have made the former Indian naval officer a global star in the world of wireless technology. **P Rajendran** profiles the winner of the **India Abroad Award for Lifetime Achievement 2013**



Professor A J Paulraj's company Beceem did a good job of competing with Intel and Samsung.

t was the abstruse idea of 'spatial multiplexing' that made Arogyaswami J Paulraj, then 48, a star in the techie firmament. That accomplishment, which has redefined wireless communication — both Wi-Fi and LTE — gave Dr Paulraj fame. For he had been churning out ideas of breathtaking originality for decades, though news of his achievement had been muted while traversing the secret military world he occupied while in India.

Dr Paulraj, now 70, is a tall man a little shy of six feet, spare of hair and an unassuming presence, and a slightly sad smile. Perhaps a legacy of his service background, he tends to dress formally. He favors his right leg, which has an artificial knee, over his tender left. When speaking, at times, he repeats the last phrase or word meditatively, using splayed fingers to stress a point — but never insistently. He is known for transforming the Indian Navy's sonar system; founding or being on the founding team of three top Indian laboratories; discovering a system the US military uses for surveillance; and coming up with the idea of splitting and bringing together data to make wireless more cost and energy effective.

After immigrating to the US after retirement from the Indian Navy, he set up two companies — which he sold to Intel and Broadcom, respectively — and bagged the IEEE Alexander Graham Bell Medal (2011) and the Marconi Prize (2014). Ah yes, he has a bagful of military decorations from the Indian Navy, is on a host of Indian government committees (which, he concedes, rarely meet), and gives lectures in universities around the world. All this, despite facing insistent hostility, rejection and ridicule for a large part of his career. Born in 1944, Paulraj was one of six children of Sinappan Arogyaswami and Rose, Tamilian Catholics who decided the family ought to stay put in their native Coimbatore while the father worked in the Indian Navy.

When 11, he was sent to Montfort School in Yercaud near Salem, an Anglo-Indian school that emphasized sports over academics.

Paulraj was mild-mannered, retiring and of an academic bent, and he had some difficulty with things like the long jump, which called for careful coordination. He participated in cricket, athletics, football and hockey, and even liked boxing a bit, but his





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INDIA ABROAD AWARD FOR LIFETIME ACHIEVEMENT

SALMAN RUSHDIE (2006) Novelist

PADMA DESAI, JAGDISH BHAGWATI (2007) Economists

ZUBIN MEHTA (2008) Conductor

SONNY MEHTA (2009) Publisher

MADHUR JAFFREY (2010) Actress

ANITA DESAI (2011) Novelist

NATWAR GANDHI (2012) Then District of Columbia CFO ROMESH WADHWANI (2012) Billionaire Entrepreneur and Philanthropist

Arogyaswami J Paulraj

For his many services to the Indian nation; for revolutionizing wireless technology; for his pioneering contribution to Wi-Fi and 4G systems; for changing the way we live.

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heart clearly lay in other things.

"I started teaching myself math," he said. Given the paucity of suitable material in the library, he began learning from the supplementary Clark's Tables which, along with logarithmic tables, also tossed in a few formulae at the back.

"I was clearly the academics guy. I was obviously considered way beyond the normal," he says, adding that when the Russians sent up Sputnik in 1957, classmates joked that he would be kidnapped either by the Russians or the Americans to give themselves and edge in the space race.

fter he topped the state exam in the sci-Alences, Paulraj's father suggested he go into the Indian Navy. Neither of them knew of the Indian Institutes of Technology, though there already was a campus at Kharagpur and the one coming up in Madras.

He had begun studying at Loyola College in

Chennai, but left in four months after his admission to the National Defence Academy, Khadakvasla, Maharashtra, came through. That was in December 1960.

He had no reason to dread the hazing that was commonplace in the academy then.

"I escaped much of the punishment by doing the homework for my seniors," he says, with the characteristic low laugh. People often told him he was not a good fit for the navy.

"Those days I was not aware what the world offered so I thought I was OK," he says. Then, in the NDA he got interested in horse riding and thought he ought to join the army.

"The armored corps," his wife Nirmala interjects. "Armored corps," he repeats, adding that it was his father who pointed out that the armored corps offered no

prospects to someone with his interests. The navy did. Paulraj graduated from the NDA in December 1963 at the top of his class, was a cadet on the INS Tir for a year spending two-and-a-half years at the Naval Engineering College in Lonavala, where he got to learn some advanced math.

There were "textbooks in advanced calculus and advanced algebra. I remember the words 'Boolean algebra (and) analysis-limit functions," he says, but there was no degree at the end of it all. He went to electrical school in Jamnagar, Gujarat, where he learned about radars and sonars and guns

Clearly looking ahead to a career in maintenance, he began work on the INS Darshak, a survey ship that used echo-sounding to map underwater areas for India's Oil and Natural Gas Commission.

Soon the navy gathered that Paulraj would be more useful with a higher education and decided to send him for an MTech at IIT-Delhi. The institute was reluctant at first, but Professor P V Indiresan (later the Director, IIT-Madras) got



When 11, A J Paulraj was sent to Montfort School near Salem, Tamil Nadu, a school that emphasized sports over academics

> involved, and got the IIT senate to approve Paulraj's induction into the program.

"After I joined, immediately (Professor Indiresan) felt I should do a PhD. He said, you already seem to know everything at the MTech level ... Originally, the navy was begging the IIT to take me." Now Professor Indiresan was requesting the navy to let Paulraj do a PhD.

The navy immediately said, no, we don't want scientists in the navy," said Paulraj, describing how things were like then, and adding that even he thought a PhD was not a very good fit in a naval unit.

"It went up to the vice-chief of naval staff (Vice-Admiral N Krishnan) and... He famously wrote in the file: We don't want scientists in the Indian Navy."

Paulraj finds it funny now and laughs outright. Professor Indiresan would not let up, and wrote back,

'You'll never regret letting him do his PhD.'

Finally, the navy said that since they had already given Paulraj two years to do his MTech, he could do whatever else he could in that period.

So Professor Indiresan responded that Paulraj would complete his PhD in two years.

It was during his time in Delhi that Dr Thomas Kailath, a professor at Stanford, visited the campus and gave a talk on his area of research. Paulraj based his work on Kailath's work, addressing ways to extract the best signal possible from a mixture of signal and random noise.

"Most use standard math but when things are not straightforward," says Paulraj, sometimes advanced math is called for, and then tosses around terms like stochaistic calculus and diffusion theory.

"My PhD thesis was at 50,000 feet high. It was very hard for anyone to read unless they knew a lot of advanced math," he says.

When the two years were done, he still had to submit his thesis, and asked the navy to keep him in Delhi till that was done.

While he was still there, India and Pakistan went to war.

And on December 9, 1971, the night the INS Khukri, the ship with India's most advanced sonar at the time, was sunk by a Pakistani submarine, the navy called him back.

"I was taken to Bombay (and told) we've just lost our top anti-submarine ship, *INS Khukri*. Sonar couldn't detect (the submarine that sank it)," Paulraj says. "I went back to IIT-Delhi to do a project that was completely practical, nothing to do with mathematical theory."

Because no other advanced nation would share its sonar with India, he was given the job of coming up with a good one

Sonar works on the argument that one can judge the distance and shape of objects from the sounds bouncing off them. But Paulraj had multiple problems to resolve before he could get all of the navy's

ships refitted to handle another such attack.

One issue involved the Doppler effect — which, as one notices when a train is coming or going away from you, can result in sounds rising and dropping in pitch, respectively. The effect came into play if sonar operators were not aware of the motion or direction of their vessel. The standard solution - making the receiver really wide - also meant dealing with extraneous noise that could obscure signals bouncing off enemy vessels.

Then there was the problem of enough sound bouncing back from the surrounding water making signals bouncing off the target hard to find. Among other things, Paulraj tried to improve the location of the target by two methods:

He allowed for his own vessel's motion in the calculations, thus correcting for the Doppler shift. This helped make the receiver bandwidth narrower. This also reduced the extraneous noise, making the sound bouncing off the enemy submarine stand out in the generated images.

The next problem was reverberation: The sound pulses from his own vessel bouncing back from irregularities in the surrounding water, a phenomenon known as backscattering, which obscures the submarine echo. If the submarine is moving at all, he rea-

soned, there would be a Doppler shift, changing the pitch of the sounds coming back from it and making it stand out in a background of echoes that showed no such shift. With some math, that contrast could be emphasized and the submarine seen far more clearly.

To find submarines lying low, figuratively or literally, Paulraj divested himself of the old British sonar, which a used single sound





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frequency, so that the sound changed in pitch over time throughout the transmission. Because of this, there was more even reverberation from the water, allowing the slightly stronger submarine echo to stand out.

While doing this work with a colleague at IIT-Delhi he also collected his PhD.

Paulraj's ideas were put into practice — and Bharat Dynamics Limited, a defense company, put it into production for inclusion on all naval ships. At the time the idea went into production, Paulraj headed to England for a year to work on a sonar project at Loughborough University.

"In 1974, everything was imported. If even the smallest thing failed, we had to get it from England or Russia. So we had no self-reliance at all," says Paulraj.

When he suggested to his navy colleagues that in the United Kingdom he could get ideas to improve systems, they told him to forget it and go and have a good time instead.

"I had modified sonar, but the navy had gone out to buy the best available sonar for future ships from France and England," Paulraj says. Naval headquarters suggested that he go over and see what the foreign sonar companies were building. Paulraj went around the installations and found them wanting, even in one case having to set right a firm that had hopelessly missed out some basic elements of sonar-marking. All of this was recorded in the Indian Navy's official history of that period.

Navy's official history of that period. And while having "lots of fun" building a minicomputer, Paulraj also concluded that India had no need to outsource work on sonar.

"I felt it was do-able ourselves," he says, adding that his superiors were initially skeptical, and worried by the fact of the effects of playing with sonar, a very large — and undoubtedly the costliest — item on a ship. The Russian sonar came in 38 cabinets of electronics, filling the space of two large rooms and cost hundreds of millions of rupees.

"Vice-Admiral (*Gulab Mohanlal*) Hiranandani (*then director, combat policy and tactics and, later, the Indian Navy's official historian*), backed me," Paulraj remembers, "but said, 'Paul, you're playing with fire. We back you and you don't deliver, we'll be left high and dry. We'll be left with ships without sonar... like a person without eyes."

Paulraj began work at Kochi but India's Defense Research and Development Organization, which ran things there, was not sure if he was up to do some real science.

"DRDO saw service officers as bringing a service viewpoint... not to be scientists," he says. "So when I went there I wasn't given any technical responsibility. I think I was made library officer. Even though I had a PhD and had built a sonar it was hard for them to (*accept me*)."

As he spent more time joining them, and after he fixed a damaged computer that had come in from the US, the DRDO officials concluded there may be more to the retiring young man with horn-rimmed glasses.

In 1976, he was put in charge of the Naval Physical Oceanographic Laboratories to put together the Advanced Panoramic Sonar Hull mounted sonar.



"We had some contact with the Americans, who had top sonar (*equipment*). They said, Paul, it's not easy to build this system... Will you have the team to build this?" He did.

"When in (*the early '80s*) we first went out to sea with that sonar, it was probably the most advanced (*ship-based*) sonar in the world in that class. It was far ahead of anything the Russians or the Europeans had; there was no question about that... My opinion was that it was ahead of the Americans," Paulraj says quietly.

He points out that while money was poured into top talent and equipment in sonar companies in the US, "We, with incredibly little money, managed to at least equal them, if not exceed them."

He sees the six years he spent working on APSOH — not the more famous projects that made his name later — as his best work.

"It wasn't one idea like MIMO, which took off and became a big fire. That was hundreds of ideas almost every day," he laughs with remembered pleasure, "but nobody knows about it. It's probably still secret."

"...After that the Indian Navy never had to import sonar technology. The group that I built became the core and APSOH... has remained the backbone of the Indian Navy. If you ask anybody in the navy (*about*) sonar, they'll say, we're self-sufficient. That is the only area we are world-class and self-sufficient."

Paulraj's scientific supervisor was then DRDO chief V S

Arunachalam, who helped him where he could to tide over some of the problems he faced.

He laughs as he describes the many political issues between Bharat Engineering Limited, the producing agency; the DRDO, the design agency; and the Indian Navy, the user.

Given his success with sonar, Arunachalam suggested Paulraj ought to head India's Light Combat Aircraft project but differences between the directors of the program saw to it that he finally did not.

According to Admiral R H Tahiliani, writing in *Quarterdeck*, a magazine for retired Indian Navy personnel, 'Dr Arunachalam was keen to get Paulraj to co-lead the LCA program, but Paulraj's suggestions for a less cumbersome administrative structure did not get the final approval and Paulraj moved on...'

He even had begun studying flying to be better prepared and Arunachalam suggested that he take a sabbatical.

"(He said) no more sonar. You can do bigger things," Paulraj remembers.

When the navy seconded that view, he thought of Dr Kailath, whose work he had expanded upon during his PhD. But he was still intimidated by Kailath's reputation.

"Going to Stanford was out of question. Here was I, a naval officer, with (*a PhD from*) IIT-Delhi, which in the world rankings (*stands*) very low. So (*I thought*) nobody will take me there," says Paulraj, but Arunachalam asked him to try, nonetheless.

^{*}I wrote to Professor Kailath. He immediately said no. He was the external examiner for my thesis. He was very impressed by my thesis but he knew I was doing engineering work building sonars — nothing mathematical. He said you're a real engineer and out of touch with all this (*theoretical*) stuff I do here. I wrote a third time, saying, I'm free. He didn't have to pay me. All I need is a desk in his office. Finally, he said, come along." That was in 1984.

At Stanford, the engineer switched back to pure theory, extending his work on sonar to see how to better use a group of antennas to locate the direction of signals coming at it. The methods in use were not as effective.

While at office at 2 am - a common time for Paulraj to be there - he came up with ESPRIT (Estimation of Signal Parameters by Rotational Invariance Technique), a way to mathematically string together a graph of the arriving signals in which the peaks would provide

observers with the best estimate of the direction of arrival.

When he came back (later to Toronto) to a conference, there were six parallel sessions on ESPRIT.

In 1986, back in the Indian Navy, he was asked to take over DLRL (electronics warfare). Advisers said there would be a lot of bureaucracy there — he was just 42 and could not take on the entrenched seniors. Arunachalam asked him to do something on his own.

So he started the Center for Artificial Intelligence and Robotics in Bengaluru. He was also on the governing board of the Pune-based Center for Development of Advanced Computing and worked on the





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software end there. He liked both because then they were startup labs.

But it was his work at BEL's Central Research Labs that actually made it untenable for him to stay in India. Paulraj says the trouble began when he failed to get someone selected for job at the request of someone more powerful on the board.

"When things didn't work out he grew "unbelievably hostile, with even threat of bodily harm — which is when I wrote to Professor Kailath asking, 'Can I come back?"

In 1991, he finally left the Indian Navy. Kailath, always the dream mentor, got him a job with math professor Gene Golub on finding ways to better differentiate between two calls from phones located next to each other. The problem was of interest to the air force, where reconnaissance aircraft at about 70,000 feet try to locate the direction of different radio signals despite the loss during propagation through air.

All the signals could look equally powerful, but since they come in at different angles to the set of multiple antennas they can be separated — because they have different spatial and temporal signatures. There were problems in doing this though since the algorithms often failed, so Paulraj was asked to work out a better algorithm.

Because of his practical bent, Paulraj bought a few 900 MHz phones, put them on the same channel, and tested them outdoors. As expected, far apart, the signals were distinct, but overlapped when they got too close to each other.

"If two phones are together the signals coming in may be just a quarter degree apart. The signature is virtually similar," he says.

"But one day it was raining and we moved it into the lobby," says Paulraj. "This time, we found two guys with phones walking next to each other we could separate now. Theory said it was not possible. Then we realized it was hitting the walls of the building and coming back, and that created the ability to separate." He realized he would not have come upon this phenomenon if the team had not done the test indoors.

"Within 10 minutes I knew exactly what was going on: this scattering (*off the walls of the lobby was creating this ability to distinguish the two signals*)," he says. "But if they hit the wall and came back, there was about 60 to 70 degrees' difference in phase shift. Now the signals were very different. In presence of scattering, the signatures become random and different."

It was while having a haircut at the barber's two days later, that he realized he could put two antennas on a phone that would send out different data streams. And why not more to send more data while also making the signals even more distinct?

He knew, though, that sending data wirelessly was not always easy.

"With one antenna, I can send 1 MB through; if I want to send 10 MB, then watts (a unit of power) needed go from one to one million," he says. But if the data was split, and then emitted and collected by antenna arrays at both ends,



Left, A J Paulraj receives the Silver Medal from then Indian defense minister Y B Chavan at the National Defence Academy passing out parade in 1963 for ranking first in the Order of Merit in academic and service subjects. Right, he receives the Ati Vishist Seva Medal of the Indian military in 1983 from then Indian president Giani Zail Singh.

the same work could be done with just with 10 watts. That, in essence, was MIMO spatial multiplexing.

The idea really did not address the air force's problem. Still, Paulraj was excited enough about it and went on to tell experts that while they were working on sending two sets of radio waves at right angles to each other, merely to double information (called a QAM: quadrature amplitude modulation), his gizmo could shoot over a million times that information.

"People then were talking of going from 4 to 6 or 8 QAM... And here was some naval officer talking of a million QAM. They walked out of the hall," he says, particularly remembering someone say, "He must be crazy." At this Paulraj laughs.

Other professors also suggested he may have been a little optimistic.

"Today chips have 16 million QAM, and are going to a billion," Paulraj says, but rationalizing that while he is sure of what he saw, he should have spent more time convincing people that his idea had merit if they only took the time to check it out.

"Maybe I didn't do a sufficiently good job of that," he says. Despite applying for a patent in 1992, Paulraj was discouraged enough by the pushback to leave the mathematical proof to others.

"I began to de-emphasize this (*work*)," he says, adding that it was finally another researcher, Emre Teletar, who came up with the theoretical model in 1998.

The same year, Paulraj, instead of working on PR strate-

gies to convince people, started Gigabit Wireless, which developed the technology that became the basis for all WiFi and LTE, now standard in a host of electronic devices.

In 2000, realizing Gigabit was being used in a variety of contexts, the name was changed to Iospan Wireless. But WiFi and 4G as standards were well over the temporal horizon, and so Intel bought Iospan in 2004, reputedly for a song. The next year, Paulraj was back in business, with Beceem, which developed technologies involving WiMAX and LTE. In 2010, Broadcom bought the company, reportedly for \$316 million.

A Marconi award press release describes John Cioffi, inventor of DSL, who too faced ridicule early on saying: 'What impresses me most is how Paul endured the tremendous, pressure, turmoil and stress of people saying his ideas weren't going to work, and persevered until he found success. Such people are pretty rare.'

Paulraj is grateful for the opportunities he got in this country.

"The environment for research, innovation, technology is so much better in the United States from every point of view – culture, resources, talent," he says. "I always say that the best thing that happened to me was coming to Stanford University." While coming away from a garden popu-

lated by Rodin's statues, he says of the





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opportunities his family got at Stanford: "We still pinch ourselves all the time."

And yet he cannot forget how it used to be.

"Some people here don't like it when I say it, but the most creative time in my life in terms of ideas was actually in India when I built the sonar system. That was really a stunning achievement in India. But when I grew senior in the navy (*he smiles wryly*) things didn't work out the way I wanted."

He still sees his time at NPOL as his most productive phase.

" M y real achievement was in APSOH. NPOL a very small lab — in defense (*terms*), one of the smallest... We made a world-beating sonar. Something must have been right."

He believes that besides people trusting his judgment, he is also not very harsh, never having fired anyone and using everyone's skill to pull together a team.

"I am able to carry people with me," he says. "People stick with me through ups and downs and anybody who's worked with me before (*if I say*) come and join me, they'll come and join me."

When he left, the navy feared the team would fall apart but the fact that it did not suggests that, despite his contributions, he had built a team that could hold together on its own.

With APSOH, he says, "I was the edge of the arrow — I was driving it (*laughs self-consciously. Now*) I take a more background role, am more a mentor..."

"If you look at my students, we are more friends. One of my main jobs today is to promote — in the broad, not the narrow sense — the wellbeing and the careers of my students and see them grow up and become big. (*In the groups I've worked with*) the people who worked with me have become the leaders and I've gone into the background," he says.

Though a man given to describing a variety of "good people," he is a little critical of one lab he worked at: CDAC.

In India, WIPRO and ECIL used to build computers earlier. In the 1960s, the Tata Institute of Fundamental Sciences built TIFRAC (TIFR Automatic Computer), under Dr Homi Bhabha, which was competitive with the world, and which had a lot of new ideas included in it, Paulraj says.

["]Today, we import everything. Nothing is made in India," he says, adding that he wants CDAC to get involved in something more real instead of building large machines that are put in a room where VIPs can admire them.

"This is not a PR job," he says.

One of his passions is the development of high technology in India.

His fingers finally come together as he lists the areas: Aerospace, commercial electronics and computers, communication technologies including wireless, modern pharmaceuticals and precision instruments (CAT scans, MRIs) among other things.

"We need a skilled work force, need investment," he says,



Professor A J Paulraj, center, won the IEEE Alexander Graham Bell Medal for his 'development of multiple antenna system for wireless communications, which helped bring the power of the Internet to mobile devices.

adding that the business is risky, highly competitive, and usually involves taking on global monopolies, like Intel.

"In India, we've done a good job of pharma manufacturing. But discovery of fundamental chemicals, no. We don't have the R&D for that. (*We have*) nothing in commercial jets, in terms of ICT. We were doing something 20 years ago, but now it's all gone away. We're importing everything now," Paulraj says, pointing out that India needs to see how China and other countries have gone ahead in these areas.

"The thing is, our universities have dropped very badly. Today, even the top research institute — IISc, Bangalore itself ranks only 300th in the world. Our academic research and our scientific research have not kept pace with the phenomenal growth that has happened in the West, in China... Singapore. We have not grown very well there."

India has an advantage when it comes to industry, believes Paulraj, who is a recipient of the Padma Bhushan, India's third highest civilian honor.

"There, we are better off because all these multinationals — Qualcomm, Broadcom, Intel — have huge R&D outfits in India and they recognize the value of Indian talent," Paulraj argues. "These (employees) are very well trained. So we have a lot of people in India who are at the cutting edge of technology — chips and a variety of things — working for multinational companies."

But there were other areas that concern him.

"Research run at the university level is not great. But once these people have an opportunity to work in these companies they grow rapidly, become leaders.... We've not created our own brand names." His hand comes together in a fist, punching gently but insistently down.

"We don't have an Intel, we don't have a Microsoft, we don't have a Qualcomm or a Broadcomm. And I think (*those are*) important, too. If you're only doing a back-end job for somebody, you don't control lots of issues. We may get some salaries but the real pay-offs come from holding equity and founding companies. All those we don't get in India."

Away from work, he has a few pleasures to keep him occupied: Western classical music he was brought up with – "Beethoven, Bach, Wagner. Opera's a bit heavy for me." He prefers instrumental classical music, orchestral music, symphonies or chamber music. And then there's Carnatic music and the dance forms of South India.

"I am not an expert, but music is a big part of my relaxation," he says.

Though he likes a variety of food, he prefers Indian food, particularly at the local Amber restaurant.

He avoids heavy reading, preferring to stick to biographies of politicians and scientists. "Human interest stories about them grabs me," he says. And then there are books on development economies — discussing how countries grow. Now 70, with people still hounding him to start companies, Arogyaswami J Paulraj appears as happy as his countenance permits. "I have kind of had the best of both

worlds, but I'm proud of both," he says. 🔳



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'He's very good at going out and making friends'

'There's a difference between having an idea on paper, in theory, and actually putting together a system. Very few academics have that. Paul has that advantage and he has put it to good use,' Professor Thomas Kailath, Dr Paulraj's mentor, tells P Rajendran

n 1970, Dr P V Indiresan at IIT-Delhi (later director, IIT-Madras) invited Stanford Professor Thomas Kailath to give a series of lectures on estimation theory, an abstruse area of mathematical research.

"I said it's somewhat mathematical. I don't think anybody understood - except Paulraj — what I was talking," Kailath laughs.

Paulraj did his PhD thesis on work Kailath had covered in his lectures. And Kailath, who was one of the signatories on his thesis, had a high opinion of his intellectual protege

"I thought (*Paulraj*) was a very bright guy because, all by himself, he learned abstract mathematics and math that was quite relevant.

He learned later that in the wake of the sinking of the INS Khukri in the 1971 war with Pakistan, Paulraj had moved to Bombay to work on improving India's sonar.

"Then I lost track of him. Suddenly, in 1983, I got a long letter in longhand from Paul, saying that he would like to come and work in (my) group. I didn't reply, but he

believed in redundancy," says Kailath, tonguein-cheek, "so he had copied that letter - there was no Xerox in those days - and a second letter came. I wrote back to him. I said, I remember you. You wrote a good thesis but, from what you tell me, you've been working essentially in development for so many years. My group is mathematical so it may not be appropriate for you.'

But Kailath finally acquiesced.

"(*My team*) had moved into a new area — called smart antennas. And Paul began to get into that and, after a year or so, came up with the idea called ESPRIT. That was near the end of his stay."

"After two years, I said, you can stay on. We can get you a position of some kind here. But he wanted to go back to India." Kailath laughs quietly at the irony.

Fortunately, he says, Paulraj had a mentor in Bharat Electronics Limited, (Captain Subburao Prabhala), who gave him a free hand to set up a lab and do things his way. But Paulraj was finally no match for the more political elements and so wrote to Kailath again, asking if he could come back

Kailath had seen what Paulraj could do - and he knew how to get the best out of a team member.



Professor Thomas Kailath helped A J Paulraj – in the face of much opposition – to get a post as a professor.

John Cioffi, who invented DSL, also got pooh-poohed by his former employers before doing his PhD under Kailath and doing the work that made him an industry legend.

Kailath was more confident about helping Paulraj because at the time he had enough research money to fund him. In 1992, Paulraj began work on MIMO.

After a couple of years, Kailath helped him, in the face of much opposition, to get a post as professor, research, a post that lacked tenure, and for which Paulraj was expected to raise 90 percent of his own salary.

After being supported for more than two years, Paulraj started finding sources for his funds.

"We started a research seminar called Smart Antenna Research Group, which he ran because my interests were moving to another field (he was getting into semiconductor manufacturing)," Kailath says.

What impressed him was that Paulraj was very bright. "The (Indian) navy recognized that – everyone recognized that. He was always interested in mathematical topics, which he studied on his own. But (he is impressive) mostly because of his work in the navy, where he was given this project to develop a sonar at a time when nobody in the

world would give (India) any technology. He had a group, but he had to read the literature himself because I don't think there was anybody else in the group who could follow the mathematics," adds Kailath.

"Paul read the literature on his own, by and large because it was a classified lab. But there's a difference between having an idea on paper, in theory, and actually putting together a system. You have to get specs for the equipment that you need, find the suppliers, negotiate with them. Things don't quite work, then you have to do trials. So you get a lot of real-world experience. Very few academics have that. Paul has that advantage and he has put it to good use."

"That, with the theoretical background (Paulraj) had picked up himself, was a very powerful combination. (Then) he started Gigabit Wireless.

Kailath, who had guided the younger man past a variety of possible pitfalls, could not prepare him for this situation

though.

"The VC (venture capitalist) could see I was rather critical so didn't put me on the board," says Kailath, who remained a small-scale investor and who still believes that it was the board that let Paulraj down, leading to the ultimate demise of the company

Among other ideas, Paulraj came up with a plan to triple the 6 MHz bandwidth terrestrial stations provided for TV by splitting 18 MHz of bandwidth and sending each set in from different stations. They licensed the technology - the early stages of MIMO.

Traditional TV required 6MHz. HDTV required 18 MHz. MIT helped compress the 18 MHz in 6. Paulraj suggested 6 MHz be sent from three TV stations and recombine them. This way, without changing any of the systems people have, you can get high-definition television. HDTV never really took off but in the patent they said that the antennae need not be separated, they could be together.

same project. "(Paulraj is) very good at going out and making friends. He knows more Indian entrepreneurs in the Valley than I do. It's a very good skill," says Kailath.

Two of those entrepreneurs pushed him

to start another company. "At Beceem, the new entity, Paulraj was the CTO. (It) did a good job competing with Intel and Samsung. Intel has not succeeded in that market, and WiMAX got replaced by LTE, which then got picked up by Qualcomm, a Goliath in the field," adds Kailath.

Ultimately, Beceem was bought over by Broadcom.

Kailath speaks of how much Paulraj learned on his own, and his wife Anu Maitra interjects to describe the case of Martin Gardner, who wrote the Mathematical Games column in Scientific American and who learned the math as he





He made friends at Intel including Pat Kelsinger, the CTO. They put a group to work on the



'He created something tremendously impactful'

He is a brilliant scholar who has profound creativity, deep knowledge, and deep insight into how to apply these to come up with breakthroughs in wireless technology, Professor Andrea Goldsmith tells **P Rajendran**



Professor A J Paulraj in his office at Stanford University.

hile working for a defense company on direction finding, Andrea Goldsmith chanced upon papers by Arogyaswami J Paulraj.

"(*I realized*), first of all, these are really brilliant papers, and, secondly, I don't have the knowledge to understand them at the level of depth that I need to implement them," she says. "I think I need to go back to graduate school." Goldsmith, now a professor in the Department of

Goldsmith, now a professor in the Department of Electrical Engineering at Stanford University, says, "To some extent, his work inspired me to go on to graduate school and, to some degree, led me to where I am today."

She was still a young professor at Caltech when one of Paulraj's students, Robert Heath, called her to ask if she could give a talk on her research in wireless systems.

Paulraj was working on MIMO, his most famous contribution, and Goldsmith had some interesting discussions about new ideas to implement using multiple antenna systems. She also knew a team at Bell Labs — where she had worked while still a graduate student — that had begun work on MIMO.

"So from my perspective, MIMO was very exciting at the

time I first met Paul," she says.

When she joined Stanford in 1999 she knew a lot of what was going on in Paulraj's lab. Given the similar areas their teams covered, many of his PhD students took her wireless class, and her students, his.

She had good reason to move to Stanford, given that her husband Arturo Salz had been a PhD student at the university and ran a startup there. Besides, she, too, was an entrepreneur.

By 2007, she, Paulraj and three others had literally written the book on their pet subject: *MIMO Wireless Communications*. Though they have not written joint papers, she has been on the dissertation committee of several of his students, including Robert Heath.

"When we worked together on the book, I was impressed with how easy it was to work together, how helpful and generous he was with his time, with his ideas. And he's also a very good friend," Goldsmith says.

"Paulraj is a brilliant scholar," she says. "He's someone who has come up with revolutionary ideas. What characterizes him is profound creativity, deep knowledge, and deep insight into how to apply these things to come up with breakthroughs in wireless technology."

"At first I was a bit intimidated by him because he's just so accomplished and, at this point, well accoladed. But the more I got to know him the more I realized how generous he was with his ideas, with his time, how much he reaches out to help junior people — colleagues, students. His students have had tremendous success in their own right. Just having him as a mentor and a role model has been very rewarding."

While she knew of his work in the US, she had little idea of what he had done in India.

"(*The*) sonar (*story*) predates my interaction with him. But when I've talked to him about work he did back in India, it appears he developed revolutionary sonar technology that was a game-changer."

Asked about how she saw him as a person, she says that she was so used to seeing him dressing well that she had a small shock when she saw him chilling out during a workshop in Hawaii.

"I see him as this always well-dressed, proper professor. So in Hawaii he was there with his grandkids and I remember seeing him in a Hawaiian shirt with this little kid jumping all over him. It's not quite the same image that I'm used to with Paulraj. He was just as dignified as a person can be – in a Hawaiian shirt with a kid jumping all over him," Goldsmith says.

"He is a quiet, reserved guy, until you get to know him," she says. "The longer I've gotten to know him the more I've seen him (get) a little looser... For people who know him well, he's a warm and good friend."

She also recalled a celebratory dinner the authors of the book they co-wrote got together for at the high-end Michael Mina restaurant in San Francisco.

"Though Paulraj likes his food and wine, his preference seems to be Indian — and his wife is an unbelievable cook. He gets very spoiled at home in terms of food. This was a very fancy, expensive dinner. And I don't think he appreciated it quite as much as he appreciates his wife's cooking."

Speaking of his work, Goldsmith says, "The invention of MIMIO created a whole new dimension for wireless systems. There's increased capacity. It's made them more robust. It's rare in a field that's so advanced as wireless is to create something truly new. And he created something not only truly new, but tremendously impactful on the theory and practice of wireless. To some extent, all the high-performance systems we have today have been influenced by his work."

She said she also admired his quiet tenacity.

"He's got a great job here (*at Stanford*)," she points out. "He did a startup (*Iospan*) that didn't work out as he had anticipated. To go and do another one (*Beceem*) and say, OK, it didn't work out the first time, but I still have this great idea which I think is going to be commercially successful and I'm going to do it again, takes a special person who isn't deterred by failure..."

"If he hadn't done that, who knows how successful MIMO would have been? Even if WiMAX is not as successful, LTE (Long Term Evolution) would not have been as fast if it hadn't been (*competing with WiMAX*). WiMAX started to get traction and people started to realize that the LTE standard looks a lot like WiMAX. It served a very important purpose in the evolution of wireless technology."

"If Paul had not done Beceem, who knows if WiMax would have got the traction that it did? There are many things about his experience, probably going all the way back to India, that shaped what he was able to accomplish later on." ■



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'He is the pioneer'

Sriram Viswanathan, who helped Intel buy IoSpan, Dr Arogyaswami J Paulraj's first company, and invested in his second company, Beceem, tells **P Rajendran** why he has tremendous respect for the scientist's ability

hen Intel wanted to raise the stakes in its wireless gamble, it went shopping for companies already developing promising technologies. One of its intrepid scouts at the time was Sriram Viswanathan, then managing director, eHome & Broadband Sectors. Serendipitously, Viswanathan had been an intern at the Indian Institute of Science-Bangalore, during the short time that Dr Arogyaswami J Paulraj headed it.

Viswanathan was no stranger to Dr Paulraj's reputation for brilliance, quality, and integrity — and so felt more confident about Dr Paulraj's Iospan than others did.

Viswanathan had taken a circuitous route to Intel — working at Wipro on Motorola's TCP IP, and working as a consultant for IBM, Chrysler and Ford, before joining Intel in 1993.

Intel decided to opt for the 802.11 standard (which later became WiFi) over the Home RF technology, primarily because the former was an IEEE standard and was using the unlicensed 2.4 GHz spectrum.

That decision, combined with launching of Centrino laptops in 2003, drove the adoption of WiFi.

Viswanathan, part of the core team looking at the market and business development of WiFi, studied various technologies and concluded that Iospan's MIMO technology was closer to what Intel thought was relevant. "It so happens, at Intel... we valued the technology. We

"It so happens, at Intel... we valued the technology. We had tremendous faith in what he was building, and we acquired that company and used that technology to build other things," Viswanathan says. Given that Iospan was not doing too well and that many experts had rejected it, Intel could acquire it cheaply. "In large part," Viswanathan says, "you have to take a bet."

"And we did due diligence on the subject," he says, pointing out how Intel was trying to increase the information that could pass through wireless.

"The constraint in the early days was with what wireless could provide; now the bottleneck lies in the wired access. The shift has much to do with Dr Paulraj's technology," he says.

"I'd seen what Dr Paulraj had done in his old career. He is the guy who did the Indian sonar in the Indian Navy. Given my history with him, I had a tremendous deal of respect for his technical capability," Viswanathan says. But he recognizes the innovator's limitations.

"I don't credit Dr Paulraj with the ability to build a business, but any day I trust him as being *the* man who knows how wireless technology works. Iospan, his brainchild, which had his most amazing technology, went bankrupt... Literally ran out of money."

But he had confidence in what Dr Paulraj had to provide.

"I was also an (*early*) investor in Paulraj's second company, Beceem, which was doing chipsets for taking 4G technology forward," Viswanathan says.

"Dr Paulraj always has a tremendous grasp — he is the pioneer — of wireless technology," he says. "When the right things line up, and when the right sort of support comes behind that, that can be industry changing." \blacksquare



PRESS INFORMATION BUREA

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Professor A J Paulraj receives the Padma Bhushan, one of India's highest civilian honors, from then Indian president Pratibha Patil in 2010.

'A tough and committed scientist'

'I would rank Dr Paulraj as one of top 10, 15 scientists in the world in wireless technology,' says Professor **Ashok Jhunjhunwala** of IIT-Madras

don't even remember when I first met Dr Paulraj; I think I probably know him forever. Perhaps it was the early '90s, I think he was still in the Indian Navy when I and Bhaskar Ramamurthi (*professor of mechanical engineering at IIT-Madras*) met him.

Since then, he has been one of our closest friends and advisers. He was a person who always encouraged us, believed in India and Indian technology.

He also believed that telecom could make a huge difference in India. He wanted every village in India to have telephony and the Internet.

In that sense, we were totally allied as that was also our mission.

At that time, we had started working on Digital Signal

Processing and Digital Answering Machine and started talking about wireless. He had come to the Indian Institute of Technology and from that day, he has been a constant guide, all the time encouraging us; in fact, almost adopting us as youngsters who could do something for the country.

He gave us the cushion; backed us in our highs and lows and gave us the confidence to move ahead. When we were criticized, he would come and meet us and boost our confidence with his words. He was a part of us and was there when we needed him.

He then went to Stanford and started working on MIMO (Multiple Input, Multiple Output), but we were in constant touch throughout. Dr Indiresan (former director, IIT-Madras) and him were the two people who wanted telecom

and broadband and IPR (Intellectual Property Rights) to happen in India. The whole concept of a Center for Excellence in Wireless Technology emerged from his thoughts. He may not have played

a direct role in it, but he was instrumental in it happening in India. 4G is what it is with him playing a major role.

If he has gone to the US and worked there, it is India's loss. But he has also contributed immensely from there. So in some sense, we never lost him, he has always been there for us. He is the person who said India should not be just a user of technology, but an owner of the IPR.

We used to meet at least 10 times a year or even more. Once he went to the US, we could meet once or twice a year or some-







'He's a patriot... His departure is a loss for India'

oasting is the mark of the real coffee guy," Rays P K Menon, a friend of Dr Arogyaswami J Paulraj from the time he first worked at Stanford. And by that measure, Paulraj is certainly one of them, he says.

"He loves coffee. He makes a fantastic cup of coffee. He grinds his own beans and roasts them," Menon says.

Menon also describes Dr Paulraj – who, during a shifting conversation, he called Professor Paulraj, Paulraj and Paul - as a serious and retiring type, reluctant to talk about himself, but someone who could make "very, very interesting presentations" with a keen sense of history, including the history of technology, about which he was much more quick to talk.

Menon and his wife Prasanna first met Paulraj and his wife Nirmala at an event Stanford Professor Thomas Kailath has organized. When it turned out that one of Prasanna's friends had been a good friend of Nirmala while growing up, the ice was broken.

"I was impressed with Professor Paulraj for many reasons. He was in the Navy – a uniformed person. He was very young at the time and he was already a commodore. A commodore (*there*)," explains Menon, "here in the US would be a Rear Admiral Lower (*half*), RADML... It's a one-star admiral in the United States. And he has this advanced degree, a PhD."

"I was more impressed because he actually came from the NDA (National Defence Academy). Normally National Defence Academy individuals are not known for any academic achievement... Their focus is different: (to try and) To create officers who are basically going to command squadrons, not go and do research."

To encounter someone like Paulraj, then, was a revelation. "Here was this very unique individual who was in uniform (but) could also do scientific work – advanced scientific work, research. I found out later he was able to go through a PhD program at IIT, Delhi. I have never met anybody like that. Right from the get-go it was clear to me he was very unique... Most people in uniform (in the Indian Navy) stop at a master's degree... or they go to (the Defence Services) Staff College and get advanced qualification in administration.

Given Paulraj's achievements and rank then, Menon had expected the naval officer to do particularly well.

When A J Paulraj served in the Indian Navy, P K Menon thought he would be the admiral commanding it one day



Professor A J Paulraj, center left, with then Vice Admiral Robin Dhowan and Commandant National Defense Academy - now Admiral and Chief of the Naval Staff – after delivering a lecture to cadets in 2008.

"I always thought that he would be the admiral commanding the Indian Navy because he had the ability, he had the education, he had the stature, background, skills and everything," Menon says.

"Typically a commodore, at 48 will definitely become the admiral of the navy by the time he's 55, which is the retirement age for an admiral. If a man like that becomes the chief of the navy, then the navy will improve, the quality will go up automatically. He has leadership abilities: He gets along with people, he knows how to form groups and leaders and so on."

Menon lost touch with Paulraj when he moved to Georgia to teach at Georgia Tech, but soon returned when his wife began pursuing a residency at Stanford University.

"In the meantime, something happened in India - I don't know what happened — and I find Paulraj back in the Bay Area," he savs

He describes Paulraj as a person who gained much from his diverse experience, as 'a guy who can combine pencil-paper work with hardware. Because he worked in the naval laboratories he has a deep understanding of communication systems and communications theory. He also understands the practical aspects of the problem," Menon says.

When the MIMO breakthrough came, the floodgates opened up for a lot of new technology, says Menon.

Nobody sees spectrum bandwidth as a limitation any more. The starting ball was from Professor Paulraj. In the case of Paul, everything just kind of lined up," he says adding that, he did not believe Paulraj could have come up with MIMO in India.

Speaking of Iospan, Paulraj's first company, Menon says Paulraj could have sold his company early on - when the dot.com and

wireless booms were both on. "At that time if Paul had cashed out his com-

pany he'd have been a billionaire. He was offered \$500 to 600 million for his company,"

Menon guesses. But the window of opportunity quickly swung shut and Iospan was left with just intellectual property, which Intel gratefully took over.

Talking about Paulraj's relationship with India, Menon said, Paulraj was "not in the right time at the right place."

"He's a patriot ... (His departure) is a loss for the country," says Menon. "Maybe it's our gain (in the US) because we're able to have MIMO, WiMAX and so on and so forth. Looking back, you can say these things happen all for the best, but at that time it didn't look like that – a senior naval officer had to retire before he could become an admiral."

- P Rajendran

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times even four times. He played a large role in advocating India's need to have its own IPR, and broadband in every village.

He even took the leadership role and said that he would work with the government to achieve that. He became a forceful person saying India had the capability and could do it.

He gave us the understanding about how to move from science and technology, from research and development, to what happens

'A tough and committed scientist'

when it goes to standards, IPR, and the royalty inflow-outflow. He was behind many policy decisions from the government.

He was part of many of the government committees and was a chairman of quite a few and we used to go along with him to meet the government secretaries. He made our task easier and it would have been tougher without him.

I would describe him as a very nice person, soft spoken but a tough and committed scientist. He knows how to take science and

technology all the way to the products. If we had adapted WiMAX technology, we would have been far more advanced and ahead in the world. He was very keen that we adapt WiMAX.

Even at this age, he is full of energy. I remember once Bhaskar and I wanted him to review our department, which meant he had to come here from the US and review it. We were not sure whether he would agree to it, but he was very prompt in telling us that he would. The way he did it

by talking to so many faculty and students and making a review at this age is worth mentioning.

I would call him one of the best scientists in India, and rank him as one of the top 10, 15 scientists in the world in wireless technology. 🔳

Professor Ashok Jhunjhunwala is a professor in the Department of Electrical Engineering at IIT-Madras. He spoke to Shobha Warrier.



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Through the eyes of someone who knows him best

Nirmala Paulraj tells **P Rajendran** what Dr Paulraj is like outside his lab

r Arogyaswami J Paulraj may appear quiet yet inscrutable to many people, but his wife Nirmala always knew exactly when things went very wrong at work. "Whenever he is stressed he gets physical problems," she says. "His knees gave out. He doesn't show emotion — get angry — (but) it shows in his body. Every time he has a serious (problem) I know because something goes really wrong in his body. (Laughs) His immune system shows what

is going on in his (*points at the head*)." Nirmala, who is more outgoing, does not mind much.

"I'm used to it," she says, describing how her father, Brigadier R A Rajan, was compelled by service rules never to discuss work issues at home.

Paulraj and Nirmala met at social occasions in Delhi, since they were from the same tiny group of Tamil Catholics, and because he was at IIT-Delhi and she was studying at the Lady Sriram College there.

But the marriage was decided by their families. The father of one of Paulraj's relatives who had married Nirmala's uncle thought the match would work. Her father wanted someone from the armed forces for his two girls. So Paulraj fit the bill. The second daughter, Hema, went on to marry an officer in the Madras Sappers.

Her father also insisted that every girl ought to get a bachelor's degree in education or go for medicine, particularly if they were going to marry service officers, which



was why she was in Delhi.

Paulraj and Nirmala were married February 5, 1973, in Secunderabad, with relatives taking expensive flights over to avoid their trains being waylaid by Communist guerrilla groups active in the area.

At IIT, she was impressed that her husband's uniform earned him a respect mere students could not get. And as time passed, she got used to his quiet nature, workaholism and absent-mindedness.

She discusses a story about him preparing to go off for a meeting on his trusty Lambretta scooter. He put on his helmet, went downstairs and then came right back up to ask for his keys, which he had a tendency to lose. After hunting desperately he was in despair about how he would make the appointment. Until he thought of looking in the helmet — where he'd kept the keys to avoid losing them.

She said they had a nice social life, especially while they were based at the Southern Naval Command in Kochi.

But Paulraj did tend to say goodbye to the hosts and then ride off alone, leaving her behind.

"I learned early on to do things on my own," she says and jokes about the time when a Telugu couple saw them, the woman told her husband in their native tongue, not realizing Nirmala was a South Indian, too, "This is the lady who comes and sits alone for movies."

"He'd drop me at the movie and go to the lab. He'd finish and pick me up," she says with a shrug, palms upward. "I don't mind. It became part of my life. (*But*) for them it was: 'No lady goes alone for a movie."" Nirmala cites what Dr Sanjay Gupta

said on CNN about the long hours he keeps: 'I steal from my family.'

Usually navy families would be back home together by 2 pm.

"(*While other*) couples sat on the verandah drinking tea, he would be out (*at the lab*)," she says.

But that wasn't an issue for her.

"I didn't make him feel guilty." She laughs and turns to Dr Paulraj: "Isn't that true?"

She says, "As you grow older you have more expectations. If you are young, (*you accept things as they are, say*) this is the life, and you carry on." \blacksquare

'He's very good at going out and making friends'

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went along.

For all his achievements, back in school Kailath himself used to only squeak by in math, though he excelled in other subjects. For a change to come about, it took the presence of a tyrant of a math teacher, who told him rather significantly at the beginning of a year that he looked forward to working with Kailath because he was the first in class.

"I worked very hard and began to like math," says Kailath, now a giant in the business, and, correspondingly raising the stock of some tyrant math teachers at least.

Kailath also has been known to promote his team relentlessly for academic honors, Maitra points out.

That push, along with Paulraj's own efforts, helped him get elected to the National Academy of Engineering after just 14 years of being fulltime in the US. Usually, admission depends on 20 to 30 years of high-quality work.

Kailath describes Paulraj as a very serious workaholic, and as a kind and good-hearted person who goes out of his way to help colleagues and friends.

Paulraj has become far more relaxed in the last few years, he says, perhaps a result of a mix of being vindicated, feted by people who actually understand how he works, or being called on by industry leaders to start new endeavors. For a man of 70 who relied more on work than network-

ing skills to get ahead, that must be particularly gratifying.

