SPACE-TIME WIRELESS SYSTEMS

One of the most promising technologies to resolve the bottlenecks in traffic capacity of future wireless networks is multiple-input multiple-output (MIMO) communications and space-time processing. MIMO wireless technology has progressed from the stage of fundamental research to commercially available products within a decade. With over sixty contributors from the field, this book provides an extensive overview of the state-of-the-art in MIMO communications, ranging from its roots in antenna array processing to advanced cellular communication systems. A balanced treatment of three key areas—information theory, algorithms and systems studies, and implementation issues—has been assembled by four editors with a broad range of academic and industry experience. This comprehensive reference will appeal to practitioners, researchers, and graduate students in wireless communications.

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From Array Processing to MIMO Communications

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Professor Arogyaswami J. Paulraj, to whom this book is dedicated.

Arogyaswami J. Paulraj

It is a great pleasure to write a brief summary of the career of Professor Arogyaswami J. Paulraj (Paul as everyone calls him), whose many contributions we are honoring with this book. Paul has had an unusually varied and brilliant career, spanning several countries, technologies and roles: leading major system development projects, founding new industrial research laboratories, guiding a large university research group, starting innovative companies, and advising several large and small enterprises. This has given him a range of experiences and a versatility that is indeed rare.

His talents were evident very early. Throughout his studies, Paul was always and easily the top-ranking student. Finishing high school at age fifteen, Paul was selected through a nationwide competitive examination for the elite Indian National Defense Academy, a joint services institution, after which he chose a Naval career. The focus of the Naval engineering cadre was mostly on practical skills for maintaining weapons systems. Paul was interested in more, and self-tutored himself in subjects such as linear algebra, control theory and signal processing. These theoretical inclinations were increasingly evident and in 1969 the Navy deputed him to the Indian Institute of Technology (IIT) at Delhi, for an MTech. program. There, he quickly caught the eye of an influential EE Professor, PV Indiresan, who urged the Navy to allow Paul to enroll in the Ph.D. program. After opposition both from the IIT Senate (which worried about Paul's academic preparation) and from the Navy (which did not see the value of a Ph.D. degree), Indiresan finally got his way. That was when I first met Paul, having been invited by Indiresan to give a few lectures at IIT Delhi on my current research on nonlinear estimation theory. To be frank, the lectures were too mathematical for most of the audience, but the challenges caught Paul's fancy. And despite some mild discouragement from Indiresan and from me, Paul persisted. And a couple of years later I was very happy to serve as an external examiner for

his PhD thesis on the estimation of Markov processes using advanced results and tools from stochastic diffusion theory.

The first pay-back for the Navy from Paul's advanced studies came sooner than they expected. In 1971, a brief war with Pakistan exposed the shortcomings of the Navy's (British origin) sonar units, leading to the loss of an Indian ship. The Navy flew Paul to a postmortem the next morning, which led to his being put in charge of a sonar-improvement project. Paul did this very successfully, working in a new laboratory set up at IIT Delhi and two years later the redesigned sonar units entered fleet service. Paul's reward was a year as a research fellow at Loughborough University in the U.K. On his return he was charged to lead a very much more ambitious project to develop a large surface-ship sonar unit, which was not available to India because of military export restrictions. Paul and his team worked under very difficult circumstances and overcame many technical (and bureaucratic) challenges to induct into fleet service in 1983 a world-class sonar system (called APSOH for Advanced Panoramic Sonar, Hull mounted). This landmark military electronics achievement in India won him several major service awards and commendations. The reward this time for Paul, by now a Naval Captain, was a two-year fully-paid sabbatical anywhere he wished in the world. I had lost track of Paul soon after his Ph.D. and did not know of his sonar work till I got a letter from him in early 1983 asking to spend the time at Stanford. After much skepticism, given Paul's more than ten years in system development, that he could fit into our pretty theoretical research group, I did agree to his request. Of course, I should have known better. Paul settled very quickly into our academic research environment and significantly helped to advance our group's recently initiated research in the area of subspace methods (launched by Ralph Schmidt's invention of the MUSIC algorithm) for direction finding using antenna arrays. In fact, just before returning to India in 1986, Paul came up with a completely new idea for direction finding called ESPRIT (Estimation of Signal Parameters by Rotational Invariance Techniques). Paul urged Richard Roy to adopt this topic for his thesis research, and their work led to a mini-revolution in subspace methods. It has spawned more than 700 papers and several doctoral dissertations; its applications go beyond array signal processing to spectral estimation and to model-based system identification.

Back in India, Paul was charged to start a new R&D center in Artificial Intelligence and Robotics in 1986. He focused it on developing command post systems for the armed forces and in parallel (!) worked on initiating an avionics development group. In 1988, he was invited to join Bharat Elec-

tronics (India's largest military electronics company) as chief scientist to set up a new Central Research Laboratory (CRL). Paul determined to introduce the structure and work culture that he had seen in the U.S. and CRL soon attracted a very bright group of researchers who developed several leading-edge products for these communication and radar systems. Again, in parallel, he set up and ran a systems software group in Bangalore for the Center for the Development of Advanced Computing, whose charter was to develop a massively parallel computer, again a technology that India was unable to acquire from elsewhere. However, administrative duties and bureaucratic battles began to take their toll and in 1991 Paul inquired about the possibility of returning to Stanford. At the time, our major funding was in a different area: a DARPA-sponsored project on the application of control and signal processing techniques to problems in semiconductor manufacturing. This time I was wiser and quickly welcomed Paul's assistance, and he and his family returned to Stanford in late 1991. By then our research in the antenna array area, which Paul had helped to accelerate before he left in 1986, had reached a stage of maturity. So with Paul and Richard Roy, now a research associate, we began to explore its applications to the re-emerging field of wireless communications. The challenges here were very different from those in direction finding, because the communication channel was much less well-defined and the earlier central concept of array manifolds became much more tenuous. Fortunately our research sponsors (DARPA) were quite open-minded and the success of our efforts in the manufacturing area allowed us to devote some resources to exploring the wireless area. This support was augmented by gift funds obtained through friends at Qualcomm, AT&T Bell Laboratories, GE, and Rockwell. The work progressed well enough that after some effort a faculty appointment as Professor (Research) came through in early 1993 and Paul began to lead an independent research program, dubbed the Smart Antennas Research Group (SARG), specifically to explore the brand new field of using antenna arrays in mobile wireless communication.

Paul attracted brilliant researchers and visitors to his group and together they developed many key ideas in smart antennas. An early Ph.D. thesis studied algorithms and system performance for Space Division Multiple Access (SDMA), which after some ups and downs is now a candidate for 4G mobile networks. In a 1993 patent application (issued in 1994), Paul proposed the use of spatial multiplexing for multiple-input multiple-output (MIMO) antenna systems and noted that it could dramatically increase link capacity. However, this patent first emphasized applications to HDTV digital video broadcasting, which in 1993 was facing a major capacity challenge; mobile

wireless was still largely in the analog AMPS era. By now MIMO is a major focus of the wireless community, and it is already entering many wireless LAN and mobile standards. Regrettably, in 1994, Paul's applications for research grants to study MIMO were unsuccessful and so he and his group focused on more immediate problems related to the use of multiple antennas only at base stations. Several theses followed studying algorithms and usage concepts in CDMA, TDMA, and OFDMA systems. Paul returned to the MIMO area in 1998 after researchers at Bell Laboratories had by then laid its theoretical foundations. New theses studied MIMO capacity, space-frequency coding, space-time spreading, space-time equalization, precoding, and interference cancellation. SARG also initiated an annual Stanford workshop on Smart Antennas to bring together participants in academia, industry and government. These workshops became very popular and grew into the focal event for this new field. SARG, over the past dozen years, has graduated twenty Ph.D. students and hosted over twelve postdoctoral students and twenty long-term visitors. Many SARG alumni have gone on to become important leaders in their own right. The group has produced over 300 archival research publications, an introductory book on smart antennas, and 23 U.S. patents. Paul has received a number of awards in India to reflect his long service there. These include the Jain Gold Medal (1974), Distinguished Service Medal (1974), Most Distinguished Service Medal (1983), VASVIK Award (1984), and Scientist of the Year (1985). His other honors include Best Paper Award of the IEEE Signal Processing Society (with Alle-Jan van der Veen as the lead young author) (1997), Distinguished Alumnus, Indian Institute of Technology, Delhi (1999), and IEEE Technical Achievement Award, Signal Processing Society, 2003. He is also a Fellow of the IE (India), IETE (India), IEEE, and the Indian National Academy of Engineering. Notably, his dozen years in the US also led to election to the U.S. National Academy of Engineering in 2006. More honors are certainly on the horizon.

Besides being a widely-sought plenary and keynote speaker at numerous academic and industry venues and conferences, Paul is active on the advisory boards of several research consortia and centers in Europe, India, and the U.S. He has also worked with industry on smart antenna development via major consulting and advising roles. In 1999, he himself founded Gigabit (later called Iospan) Wireless, which successfully developed a MIMO-OFDMA based fixed-wireless system. Iospan, the first company to commercialize MIMO technology, was acquired by Intel Corp. in 2003. In 2004, Paul was invited to cofound Beceem Communications to develop chip sets for the mobile wireless Internet market. Smart antenna technology, which has

now grown to dominate research and applications in wireless, owes much to Paul's contributions. He asked many of the right questions about this emerging technology and helped evolve a balanced picture of its potential and challenges.

Paul has been at different points in his career a scientist, engineer, teacher, manager, and advisor—sometimes many of these at the same time. And to everything he has brought dedication, vision, and humanity, which, combined with his scientific and technological abilities, has transformed and enhanced everything he has worked on. We are all very indebted to the editors of this book, themselves alumni of SARG, for organizing a conference and putting together this book to honor, on the occasion of his 60th birthday, the many contributions of Professor Arogyaswami Joseph Paulraj.

Thomas Kailath, Stanford, CA

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