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Report Title: Nonlinear Dynamical Beam Manipulation

Project Goal

I reviewed the available literature on nonlinear dynamical beam steering of antenna arrays. The goal was to assess the current state of development, identify the most important research groups, identify the practical advantages of this scheme, and determine any areas of opportunity that appear ripe for exploitation or further research.

Summary Overview

Nonlinear dynamical beam steering of antenna arrays as a fundamentally new concept was put forward in the 1990's independently in the engineering and nonlinear physics communities, by R.A. York in the former case and T. Heath & K. Wiesenfeld in the latter. The central observation is that it is possible to achieve desirable dynamical configurations (i.e. particular patterns of relative phase shifts among elements within the array) as a natural result of the inter-element interactions; moreover, these dynamical states can be manipulated in real time. This stands in contrast to traditional schemes using isolated (non-interacting) elements with an external control on each element, and with these individual controllers in turn centrally monitored and configured. The new approach has undergone steady development since its inception, predominantly at the proof of concept level. A central roadblock to faster development is an entrenched prejudice, namely the longstanding engineering design assumption that elements must be isolated from each other: zero interaction is the starting point of virtually all traditional analysis and design; interactions between elements are typically assumed to be necessarily bad. Research into the new approach shows that while unknown and uncontrolled interactions are undoubtedly a bad thing, certain interactions lead to desirable outcomes without the need for external control.

Advantages to Interacting Antenna Arrays

Researchers cite various advantages to having an interacting element array. Most frequently cited are the following. Some applications require miniaturized arrays (for example used in an automated collision-avoidance system on automobiles). In this case isolation of individual elements is difficult if not impossible. Miniaturization also puts space at a premium which makes it desirable to eliminate the need for phase shifters controlling each element. Even if miniaturization is not a goal, for very large arrays the cost and complexity can be prohibitive when each oscillator requires its own phase controller, and the master controller which coordinates the phase shifting of the elements is an intrinsically fault-sensitive architecture (i.e. if the master stops working the entire array is rendered useless) as compared with a design based on local interactions. Finally, for applications which require antenna scanning at very high frequencies, external steering (e.g. by mechanical means) can be either too slow or too sensitive to wear as compared with the very rapid time scales of the intrinsic dynamics of the electronic elements.

The downside is that while an array employing individual and independent phase shifters is completely flexible in generating any phase configuration, dynamic coupled arrays naturally evolve to particular configurations, and at present the number of achievable patterns is small. Neither is it known what patterns might not be possible in principle. On the other hand, any configuration that can be achieved is per force inherently stable and noise tolerant.

Dominant Research Groups in the Field

The exploration of these arrays remains relatively circumscribed; the most important recent work to be found in the published technical literature has been dominated by a handful of research groups. These groups are located at the Georgia Tech Research Institute (T. Heath) , the Jet Propulsion Lab (R. Pogorzelski) the University of California at Santa Barbara (R. York) and the United States Navy SPAWAR lab in San Diego (B. Meadows). There is also some relevant unpublished work by N. Corran, a U.S. Army scientist (indicating potential interest by the Army).

State of the Art

The basic proof-of-concept behind interacting antenna arrays has been demonstrated repeatedly, both theoretically (in simulations) and experimentally. For example, Meadows et al report results from 20 element array on low-frequency (kHz) aVLSI chip. The most advanced experimental demonstrations are those of Pogorzelski. On the theory side, a number of issues have been considered. In some cases the progress is complete, for example the generation of a constant phase gradient in static (beam steering) and dynamic (beam scanning) arrays of the sort typified by phase-locked loop arrays. Similarly, the problem of difference pattern versus sum pattern generation has been solved. By constrast, the key problems for which only partial progress has been made (and which represent areas of near-term opportunity) are those of beam-shaping/beam-forming, with particular interest in sidelobe reduction and null creation (which have both efficiency- and security-related motivations). Still less progress is available on certain other important problems -- I think it is fair to say that these are virtually wide open areas. Of these I would pick out three as most significant. The first is the demonstration (and development) of these ideas in receiving as opposed to transmission. The second is the extension of these ideas to broadband (e.g. pulsed) rather than narrowband (e.g. monochromatic) operation. The third, closely related to this, is the possibility of achieving so-called real time delay among constituent elements as opposed to phase shifts among them.

Areas of Opportunity

Three opportunities appear to present themselves at the present time.

(1) Development of beam-forming strategies. Heath has shown how to achieve significant side lobe reduction and null placement, but only in a proof-of-concept sense, using a rather difficult and practically intractable construction. This problem is ripe for theoretical progress both analytically (using a modified approach from Heath's), and numerically (using an iterative/feedback approach), to discover the desirable parameter tunings. Once the theoretical underpinnings are in place, it would be straightforward to launch into hardware implementation.

(2) Demonstration of true time delay. A scheme for achieving true time delay among pusle-like waveforms would be an important step toward achieving broadband operation of interacting antenna arrays.

(3) Demonstration of beam steering in receiver mode. It is well known that there is often reciprocity between transmit and receive modes of operation for antennas. Yet it remains unproven (and indeed unclear) that such reciprocity extends to these ideas of interacting antenna arrays.

Finally, it deserves mention that HRL already employs someone with specific expertise in this area. John Lynch did important early work on this topic while a graduate student at U.C. Santa Barbara (under the supervision of R. York).

Annotated List of References

R.A. York and Z.B. Popovic, Eds., Active and Quasi-Optical Arrays for Solid State Power Combining (New York, Wiley, 1997). *Collected papers providing deep background to the subject. Includes most of the UCSB group's contributions to the field. Closest thing to a monograph on the subject.*

J.J. Lynch and R.A. York, "A mode locked array of coupled phase locked loops", IEEE Microwave Guided Wave Lett., vol 5, pp 213-215 (1995). *Demonstrates a particular pulsed-output dynamical state which stands in marked contrast to the other kinds of* *continuous-wave output reported in other published demonstrations of dynamically coupled antenna arrays, before and since.*

J.J. Lynch, H.-C. Chang, and R.A. York, "Coupled-oscillator arrays and scanning techniques", in Active and Quasi-Optical Arrays for Solid State Power Combining (ibid), pp. 135-186 (New York, Wiley, 1997). *Lynch is currently a scientist at HRL.*

R.A. York and T. Itoh, "Injection- and phase-locking techniques for beam control", IEEE Trans. Microwave Theory Tech., vol 46, pp. 1920-1929, (Nov 1998). *Demonstrates another advantage achievable with dynamically coupled oscillator arrays, which is a reduction in noisy jitter and a concomitant increase in frequency capture range.*

T. Heath, "Synchronization and phase dynamics of coupled oscillators", Ph.D. dissertation, Georgia Tech (1999). *Heath's Ph.D. advisor is yours truly.*

T. Heath, K. Wiesenfeld, and R.A. York, "Manipulated synchronization: Beam steering in phased arrays", Int. J. Bifurcation and Chaos, vol. 10, no. 11, pp. 2619-2627 (2000). *Provides a complete and explicit analytic treatment of the phenomenon; represents the starting point for a variety of Heath's later developments including beam shaping, null formation, and fast scanning.*

R.J. Pogorzelski, P.F. Maccarini, and R.A. York, "A continuum model of the dynamics of coupled oscillator arrays for phase-shifterless beam scanning", IEEE Trans. Microwave Theory Tech., vol. 47, Apr 1999. *Presents an alternative mathematical approach to the one provided by Heath and co-workers. The continuum model is inferior insofar as it is fundamentally limited to small phase shifts between neighboring elements, but since it relies on older (linear) mathematical tools, it has the advantage of being more readily accessible to the wider audience of traditionally trained scientists and engineers.*

R.J. Pogorzelski et al, "A seven-element S-band coupled-oscillator controlled agile-beam phased array", IEEE Trans. Microwave Theory Tech., vol. 48, pp. 1375-1384, Aug. 2000. *Laboratory demonstration of beam steering in a "one dimensional" (i.e. linear) array.*

R.J. Pogorzelski, "A two-dimensional coupled oscillator array", IEEE Trans. Microwave Guided Wave Lett., vol. 10, pp. 478-480, Nov. 2000. *Represents the best existing laboratory demonstration of dynamical beam steering in two dimensions, with independent control along x- and y-axes.*

T. Heath, "Difference pattern beam steering of coupled, nonlinear oscillator arrays", IEEE Microwave Wireless Components Lett., vol. 11, no. 8, August 2001, pp. 343-345. *Theoretical analysis of beam steering in a mode relevant to target tracking applications.*

T. Heath, "Beam shaping of coupled, nonlinear oscillator arrays", (preprint 2004). *Theoretical analysis demonstrating node generation and node placement (broadside for a one dimensional array).*

T. Heath, "True Time Delay Beam Steering in Phased Array Antennas", (preprint 2004). *Clear exposition of the potential advantages of "true time delay" outputs over "phase shifted" outputs; the drawbacks of existing implementations that achieve true time delay; and a proposed (but untested) scheme that sidesteps these drawbacks using coupled-element antenna arrays.*

B. Meadows et al "Nonlinear Antenna Technology", Proc. IEEE volume 90, no. 5, May 2002, 882-897. *Good overview of their group's (somewhat disjointed) work. Group includes researchers at SPAWAR San Diego, Georgia Tech ECE, University of Florida, and the private company Information Systems Laboratories, Inc. (San Diego). They also discuss its relationship to certain neuronal and biomorphic engineering principles.*