Organized by Thomas Kaiser

When Will Smart Antennas Be Ready for the Market? Part I

The term smart antennas (SAs) was born in the early 1990s when the well-developed adaptive antenna arrays used in the military were brought by several scientists into mobile communications. (To be more precise, smart antennas entered research in civil mobile communications before the 1990s under the original name adaptive antenna arrays [1]). Hence, the research on SAs began more than a decade ago, and many scientific contributions have been published in innumerable conference proceedings and in various journals. Moreover, numerous SA testbeds were built, and more than 100 academic and industrial institutions are active in SA research in Europe alone. One of the SA pioneers, Prof. Ernst Bonek from Vienna University of Technology, periodically asks his industrial fellows about their expected breakthroughs in smart antennas in terms of successful products. The answer today is the same as it was more than a decade ago: *in two years*. But why haven't SAs penetrated the market yet? Despite all the research efforts, isn't the technology mature enough? Or do we need to conclude that there is no market need for SAs?

The aim of this forum is to shed more light on the topic from various perspectives. Before we proceed any further, we need to agree on some vocabulary. SAs are referred to as either multiple input and single output (MISO) or single input and multiple output (SIMO) systems, whereas multiple input and multiple output (MIMO) stands for itself. Moreover, the following discussions and opinions are subdivided into fixed or nomadic (e.g., indoor) and high mobility (i.e., outdoor) applications because of the different types of markets, demands, and technological barriers.

Let us start with some words about the need for SA/MIMO. Besides improvement of link quality, two major advantages of SA/MIMO are extensions in data rate and coverage. Since coverage and data rate can be traded off to some extent, we will focus our discussion for the moment on data rate only. In analogy to Moore's law, the so-called Edholm's law of data rates has recently been proposed [2]. It says that data rates increase exponentially with time, independent of wireline, nomadic, or wireless type of systems. Taking into account today's maximum rate of 1–2 Mb/s for mobile cellular systems and 10–50 Mb/s for indoor systems, we may expect in five years data rates up to 20 Mb/s for systems with high mobility and up to 500 Mb/s for fixed or nomadic types of wireless communications. But how can such data rates be achieved?

For outdoor scenarios, higher order modulation schemes [e.g., 16-QAM for Universal Mobile Telecommunication System—High Speed Downlink Packet Access (UMTS-HSDPA)] and the adaptive modulation schemes are now standardized, promising a peak rate up to 10 Mb/s. Because of the challenges caused by high-mobility channels, even higher modulation schemes are seemingly impractical. Fixed or nomadic types of systems behave rather similarly: current wireless local area networks (WLANs) have already deployed 64-QAM and wireless metropolitan area networks (WMANs, e.g., WiMAX) are even targeting 256-QAM, but such high-level modulation schemes may impose too strict requirements on the analog front end. Hence, there is a need for alternative technologies, and SA/MIMO seems to be well suited to serve both indoor and outdoor systems. Needless to say, increasing bandwidth represents another way; this may require less technological but more social efforts worldwide due to the already dense and less-harmonized frequency occupation. For example, ultra-wideband systems seem to hold promise for communications of rather short distances (less than 10 m) and data rates in the order of several hundred megabits per second, but its regularization is still under discussion in several countries ([3], Ch. 7).

(a) (b)

NAKITA DI GUARDI (BELKIN).

(a) Prestandard WLAN access point with three antennas and (b) the corresponding laptop card, available since the end of 2004.

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BJÖRN OTTERSTEN (ARRAYCOMM).

First SA base station of ArrayComm for cellular mobile communication networks (Asian PHS Standard), available since 1997.

Extrapolating Edholm's law shows that SA/MIMO technologies are not far away. Indeed, for IEEE 802.11n, there are several MIMO proposals submitted for data rates up to 108 Mb/s. A data rate of 500 MB/s is envisaged as an optional part of IEEE 802.11n, which should be available by 2007 and therefore even outruns the prediction by Edholm's law. Moreover, release 4 of UMTS includes transmit diversity, and release 6 will probably include a MIMO extension to HSDPA.

So, why such a forum? First, scientists are curious to see the scenery behind the curtain, especially the open challenges. And second, trust in forecasts is rather limited, particularly for wireless communications and exponential increase.

Following the successful scheme of previous *IEEE Signal Processing Magazine* forums, well-known experts from academia and industry have been invited to jointly discuss their views. First, the panelists replied to the key question "When will SA be ready for the market?" as well as to some more specific questions. A draft has been prepared, and the discussion has been opened among the panelists by e-mail, being condensed within this first part. The interested reader may visit the public forum at www.cspl.umd.edu/spm/smartantennas to actively participate in this debate. Moreover, at ICASSP 2005 (see www.icassp2005.com/SS_P4.asp) a panel discussion with most of the panelists will take place. Part II aims to summarize the contributions to the public forum and the discussion among the ICASSP panelists. Of course, all readers are invited to send me their opinions or to raise new questions to shed further light on the future of SAs.

—Thomas Kaiser

OPINIONS OF PANELISTS

ANDRÉ BOURDOUX

Most current wireless standardization bodies (3GPP, IEEE 802.11, 802.16, and 802.20) are discussing or have already included some multi-antenna techniques. This shows that the techniques are becoming sufficiently mature from both a theoretical and implementation point of view. Their practical and commercial use is a matter of engineering and marketing efforts.

As a general trend, we can observe the following:

- For outdoor systems, sophistication (complexity) comes first at the base station (BS) or access point (AP) side, while for indoor systems, the complexity difference between the AP and user terminal (UT) is much smaller.
- The complexity "ranking" is in increasing order: diversity (selection diversity, combining diversity, and transmit diversity), beamforming, and spatial multiplexing. Due to this ranking, this is also the order in which these techniques are expected to be introduced.

The technological effort is much higher at the terminal side because of the cost, size, and power consumption constraints. But the evolution of deep submicron technologies has lifted many of the technological barriers, and cheap, reliable MIMO terminals are feasible with the latest technological processes. This is further helped by cross-disciplinary progress that leads to system-in-a-package or system-on-a-chip realizations, possibly including the antennas on a substrate.

In addition, it is likely that future systems, starting with 802.11n, will incorporate several MIMO techniques (diversity and/or spatial multiplexing) and the MAC controller will play an important role in the best exploitation of channel resources. Most techniques considered in standards need receive CSI. The use of MIMO techniques with transmit CSI can also improve the capacity or link quality, but its adoption in standards is observed to be slower.

SEUNGWON CHOI

We address the following two questions. Do smart antennas operate off the shelf as well as expected? If not, what are the causes for the failure and how long will it take to resolve them?

The most serious technical problem is that the forward link beamforming must use the parameters obtained during the reverse link. This defect could be mitigated through an accurate autocalibration technique. The forward link operation is also degraded in multipath signal environments because of its beam pattern having multiple beams. Another practical problem is that the number of radio frequency (RF) cables connecting the antenna elements to the main body of BS is large, which results in a bunch of monster cables passing through the building on which the BS antenna is installed. This obstacle could largely be resolved by replacing the RF cables with fiber optics; this, however, would cause other undesirable features. Consequently, if the autocalibration is accurate enough and the angle spread is not that wide, SAs would provide a comparable amount of enhancement as that in reverse link.

Assuming that the mismatch between reverse and forward links does not cause the gain in the reverse link to be diminished at all, an SA BS can be put into the real market right now. Considering the period required for the integration of the new modem chip and bench-marking test (BMT) for a particular operator, however, we conclude that SAs can show up in real markets in about two years.

ANDY FUERTES

Market success remains elusive for the SA products. Though the technology can be found in over 200,000 PHS base stations, it is virtually absent from deployments of GSM, UMTS, and CDMA2000 base stations. Change may be imminent.

Carriers are rapidly exhausting traditional capacity improvements such as line card or software upgrades, and the economics of new interfaces and additional cell splitting in already saturated mobile markets are increasingly suspect. Bandwidth demand caused by data consumption and replacement of fixed services with mobile services are additional triggers that promise to prompt a greater role for SAs in the future. Virgin deployments of wireless, fixed and mobile, within emerging nations will also challenge the traditional economics of wireless.

The crossover point is now the main issue. When does the SA option become more sensible from an operator perspective than other alternatives? SA advocates may argue that this point has been with us for some time, but carriers place a high value on real estate (tower sites) and spectrum acquisition, as these latter assets are deemed scarce and invaluable. Operators in saturated markets and some emerging mobile markets have largely exhausted these options, suggesting that the next major capacity upgrades in these areas will include SA technology.

However, the individual crossover point will vary according to each operator and even according to each cell within an operator's network. That crossover point is already here in 2004 for some operators as they seek to extend the life of GSM or CDMA network equipment and enhance capacity in certain high-density areas. Thus, SA adoption within existing networks will be gradual and ad hoc. Wider acceptance of the technology within cellular networks is expected to result from demand for fast data services. Consumers in most parts of the world are just beginning to use such services, and broad acceptance of mobile Internet is likely five years or more in the future, suggesting that SA deployments will accelerate dramatically as we approach this milestone.

CHRISTOPH MECKLENBRÄUKER

SAs and MIMO are technologies that compete with other types of network enhancements. Investments in SAs and MIMO pay off as soon as the traffic demands come close to the capacity limits without antenna array enhancements. Conversely, SAs have the capability to save sites when deploying a new network. The cost structure of such investments is highly relevant to operators. The ratio between the time-averaged cost of the equipment and the costs per site define the merits of SAs/MIMO. Key technological challenges include: moving portions of the baseband processing and the power amplifiers close to the antenna array, integrating multiple antenna elements into small device volumes, and mastering the numerical complexity of signal processing and radio resource management strategies. Finally, I believe that the key benefit of SA/MIMO techniques is their ability to provide flexibly configurable communication services rather than peak data rates.

QINGHUA LI

SAs have already been on the market for more than 20 years, while MIMO systems have recently been introduced. However, both SA and MIMO techniques are not in wide use yet. Two standards, IEEE 802.16e and 802.11n, are expected to be released in 2005 and 2007, respectively, with SA and MIMO as essential components. In 2007, the standard compliant products may first gain a significant share of the laptop market.

Although SAs at large are not widely deployed, switched diversity as a simple SA technique is already in common use in WLAN and 2G base stations. Advanced techniques such as transmit beamforming and space-time codes are being incorporated into 3/4G UMTS and 802.16d/e standards. Theoretical study and system development of MIMO in the last decade cleared major technical obstacles for market deployment. A few products were already deployed in 2003 and 2004. However, additional costs, competition with existing nonMIMO systems, and delayed standardization processes prevented MIMO from penetrating the market. Since laptop is a better platform for high-data-rate applications such as video streaming, we expect MIMO on laptops may take the first stronghold in the marketplace in 2007 in the form of 802.11n and later 802.16e compliant products.

BJÖRN OTTERSTEN

Multi-antenna systems have successfully entered parts of the wireless communications market. Well over 200,000 personal handy phone system (PHS) multi-antenna access points providing spatial interference rejection and spatial multiplexing on both up- and downlink are commercially deployed in Asia, serving millions of costumers. SA techniques are already integrated into many systems in the form of diversity (receive and transmit) techniques. However, to cost-efficiently exploit the full potential of spatial processing techniques in wireless communication systems (substantial increase in system capacity), full integration of the technology in the system architecture is required. Therefore, we will see mainly diversity and interference rejection techniques in 2G and 3G systems. The full benefits of SA technology will reach the market earlier for indoor systems and systems that don't necessarily provide wide area coverage (or support high mobility). Although there has been much emphasis on MIMO link capacity, the main challenge (and benefit) of SA technology is the ability to design wireless systems that, in addition to high peak data rates, are scalable with respect to the number of wireless modems and coverage area, provide reliable service to multiple terminals, and incur a low cost.

CONSTANTINOS PAPADIAS

Non-MIMO SA technology has already been introduced in cellular systems, such as the Alamouti-type transmit diversity techniques (STTD and STS) that were incorporated almost five years ago in the 3GPP and 3GPP2 standards, respectively. However, the introduction of true MIMO systems in commercial 3G (macro-cellular) systems has so far stalled. Some technical reasons for this are

- the limited (yet justified) initial scope of no more than four antennas on each side of the link
- the operation points of CDMA systems (given by the cell's geometry), resulting in only a minority of users enjoying high signal-to-noise ratios (SNRs)
- the inherent diversity benefits of scheduling in packet data systems.

These three factors combined effectively limit the gains of 4×4 MIMO systems over simpler techniques (e.g., diversity combining, and sectorization). Some related business factors are

- operators can only profit from high-throughput solutions if there is a high demand for wireless data combined with insufficient spectrum resources (see [4])
- a large fraction of 3G data terminals are still handheld devices (mostly cell phones); this works against the will to incorporate multiple antenna elements on the terminal.

In indoor systems, the combination of wide bandwidth and short range typically results in wireless LAN terminals that enjoy very high data rates (on the order of several megabits per second), thus reducing the need for higher spectral efficiency. Furthermore, the rapid depreciation of self-installable wireless LAN access points makes it increasingly hard to introduce technologies that increase their cost. In conclusion, wide adoption of IA/MIMO technologies is likely to occur when the spectral efficiency needs surpass the available lower cost/risk capabilities, especially as viewed from the position of wireless operators and terminal manufacturers.

STEFFEN PAUL

Although MIMO is considered an important step to increase the capacity of wireless links, it has not yet reached the market for cellular systems. At the moment, the demand for higher data rates does not really exist. The progress in standardization activities is anything but fast, at least for UMTS. Several proposals for MIMO systems are on the table, but a final agreement on one specific system has not yet been reached. The technological challenges to put MIMO systems on silicon are huge. Starting with single-antenna UMTS, it no longer seems possible to run the wireless modem on a single DSP, as is the case in GSM. Several rather complex hardware accelerators are required, therefore complicating the chip design. The situation becomes even worse for a MIMO receiver. The unstable UMTS MIMO standard is an additional obstacle in the design of dedicated hardware.

The gap in design methodology and tools to quickly and reliably map algorithms onto silicon architectures seems to be another critical point for a successful introduction of MIMO. In the past, the development of receiver algorithms was mainly driven by information theoretic optimality criteria. Low-complexity issues in terms of memory requirements and low power consumption were often disregarded.

AROGYASWAMI PAULRAJ

The use of transmit diversity has been incorporated into 2.5G (EDGE) and 3G (UMTS) standards through beam forming and Alamouti-type coding. In this sense, smart antennas have either already been deployed or adopted into standards awaiting deployment. The question of when SAs will be ready for the market is relevant primarily in the context of spatial multiplexing for single-user and multi-user applications.

Single-user spatial multiplexing to increase spectrum efficiency is a powerful technique for improving capacity. It has attracted significant interest in all wireless applications: WLANs (802.11/Hyperlan), WMANs (802.16), Mobile data (802.20), 3G mobile wireless (UMTS/HSDPA evolution), and future 4G systems. This technology is also referred to as MIMO wireless since it requires the use of multiple antennas at both the transmitter and receiver. However, widespread commercial use of MIMO has not yet begun because standardization of MIMO has yet to be achieved in any area. There is current activity within 3G, WLANs, and WMANs to incorporate MIMO into the next-generation standards, and this is expected to take another 18 to 24 months. One can expect commercial products to emerge in that time frame, if not shortly thereafter. The initial applications will be in high-speed data links for laptop terminals, where multiple antennas can be easily supported for the area and power considerations. A solid understanding of the theory required to build commercial systems already exists. The main challenge for commercial deployment of MIMO is the standardization of the technology.

The application of multi-user spatial multiplexing (sometimes referred to as spatial division multiple access, SDMA) is still in its infancy. In SDMA, the base has multiple antennas, and it communicates with multiple single-antenna receivers. SDMA needs accurate channel knowledge at the transmitter (base), which is problematic in many wireless systems.

In summary, some aspects of SAs are already deployed, while others have been incorporated as optional features in standards to be activated in the future. Single-user spatial multiplexing is ready for incorporation into several standards, while multi-user spatial multiplexing will need more fundamental work before standardization can begin.

PIETER VAN ROOYEN

"Space, the final frontier," the multiple antenna adage goes. SA systems have already been commercially available for a number of years, and the question is if SA systems will continue to grow in importance in the future. There is no wireless technology in existence today that rivals the spectral efficiency achievable with multiple antenna technology. The spatial domain promises all the benefits (and more) offered by the traditional frequency, time, and code domains. It also shows particular promise as a multiple access technology. In fact, a myriad of new wireless techniques and applications await us in the final wireless frontier.

The key challenge in fueling the growth of multiple antenna technology lies in applying these techniques to the mobile handset and subscriber modules. For this to happen, the three Ps of consumer electronics need to be addressed. In order of importance, the three Ps are:

- *Price point:* In the past, SA techniques have mainly been applied as a base station or access point technology. Techniques need to be developed to reduce the cost impact of multiple antenna technology in ultra cost-sensitive equipment such as mobile phones. A higher degree of integration at the silicon level will also help to reduce the price point to acceptable levels.
- *Power consumption:* As we move to 90 nm and lower technologies, the power consumption impact of advanced signal processing and high clock rates on a mobile device become more feasible. Algorithms and techniques need to be tailored for implementation on handset and subscriber modules.
- *Performance:* Better coverage, higher capacity, higher data rates, and all the other benefits of multiple antenna systems will forever be relegated to the realm of theory and papers if the preceding two points are not addressed in earnest.

Work on the three Ps is progressing on all fronts and will take multiple antenna techniques to the next level of growth within the next two to three years.

JACK H. WINTERS

SAs are already on the market, and the question is when they will be widely deployed in a variety of systems. The key issues are the following:

- *Standardization:* 3GPP, 802.11n, 802.16, and UWB are developing standards that will use SAs, and the successful completion of these standards is required for widespread deployment.
- *Cost reduction:* The cost of multiple RF front-ends must be further reduced.
- *Economic need:* Users must see the need to pay the extra cost for the benefits of SAs, such as increased capacity, QoS, range, data rate, and interference mitigation.
- *Integration:* SAs need to become integrated into the overall system design, including radio resource management, cross-layer optimization, and networking techniques, to fully benefit from and justify the cost of SAs.

With progress in these key areas, SAs should be widely deployed in the next couple of years, providing data rates in excess of 500 Mb/s indoors and 70 Mb/s outdoors.

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