The Market Opportunity for Multiple Antenna Technology for Next Generation Broadband Wireless Systems

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Abstract

The rapid growth of the Internet user base and of bandwidth-hungry applications in recent years has created a need for broadband wireless (BW) access for residential and business consumers. The only predictable trend is that data rates and QoS requirements will increase rapidly. This demand for high-speed wireless access/connectivity is becoming a market force for advanced wireless broadband technologies and networks. One of the major technology innovations to affect the future of broadband wireless industry is the use of multiple antennas and either end of the wireless link to provide unprecedented gains in capacity, link reliability and data rates. While the expected benefits associated with multiple antenna technology are high, there is a perceived significant cost (in terms of R&D, implementation, hardware, inertial) associated with adoption of multiple antenna technology. This paper presents the results of a study of the evolving broadband wireless industry that aimed to analyze the barriers to adoption of multiple antenna technology in shaping future wireless systems.

1. Introduction

The fixed broadband wireless market (sub-11Ghz) will grow from $430 million in 2003 to more than $1.6 billion by the end of 2008. In 2003, BW shipments increased 45% over 2002 [1]-[3]. Vendors have announced both multi-million dollar contracts and hefty growth earnings compared to 2002. Technology news editors are now talking about a BW come back with the emergence of millions of Wi-Fi access points connected by more flexible and less costly fixed wireless solutions. Despite the 2001-2002 market slowdown, the steady demand for bandwidth, coupled with wider access to the Internet and data in general, provide sound fundamentals for expecting future growth in both telecom services and equipment sales in the first/last mile. In other words, both residential and business subscribers worldwide are demanding faster connections for their applications and operators are struggling to give them that access. According to the International Telecommunications Union (ITU), there were almost a 100 million broadband subscribers worldwide at the end of 2003. Although DSL and Cable are poised to remain the dominant broadband access technologies worldwide, wireless access technologies are becoming a reliable and cost effective complement or alternative to providing data, voice and video services.

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The phrase ``broadband wireless'' is constantly evolving. We segment the broadband wireless market into the following three categories and provide an overview of relevant standards activity for each segment. The concept around standardization is to reduce equipment and component costs through integration and economies of scale that will, in turn, allow for mass production and hence less expensive equipment. Thus, we limit our research to the context imposed by the following standards, though we note that proprietary non-standards compliant solutions will co-exist to serve niche markets.

Emerging BW (IEEE 802.16 d/e)
In early 2003, the IEEE, responsible for setting global communications standards, approved the 802.16 Wireless MAN (Air interface for Fixed Broadband Wireless Access Systems) interface communications protocol, which uses the 2 to 11 megahertz frequencies. This move followed IEEE approval of the parent 802.16 protocol in December 2001 for point to multi point architectures at greater than 11 megahertz frequences. The standard covers both the Media Access Control (MAC) and the physical (PHY) layers. The WiMAX Forum, a non-profit trade organization, was then founded in April 2002 to promote interoperability between different vendor equipment. The standard developed was approved by the IEEE-SA Standards Board in June 2004 and will be published as IEEE Standard 802.16-2004. Approved in February 2002 by the IEEE, the 802.16 e standard is aiming at providing broadband access to the mobile user walking around with a PDA or laptop while a different standard (IEEE 802.20) will address high-speed mobility issues. The corresponding standard is expected to be published late 2005.

WLANs (IEEE 802.11)
The network systems known as Wireless Ethernet, 802.11x, W-LAN or Wi-Fi (all names for the same technology) are rapidly becoming a popular means of networking devices over a wireless local area network (LAN). The IEEE 802.11 standard uses the Industrial, Science and Medical (ISM) band, which is available for unlicensed operation practically all over the world. The basic W-LAN network consists of an access point (usually wired into the internet) and mobile client computers. The network operates in a star topology with the base station bridging communication between computers and communications onto a wired network (either a wired LAN or the internet). As the technology has developed, so too have organizations such as the Wi-Fi Alliance which certify interoperability of IEEE 802.11 products and promote the technology as a global standard. The original 802.11 standard was finalized in 1997 with 2 megabit per second data rates but it was not a commercial success until 1999 when 802.11b with 11 megabits per second throughputs was introduced. Later enhancements including 802.11g and 802.11a provided fifty megabit per second throughputs. Work on the high speed standard 802.11n began late 2004 and is expected to offer hundreds of megabits per second thanks in part to multiple antenna technology.

3G Cellular
Few new technologies have suffered such a dramatic rise and an even more dramatic decline as has been experienced by third-generation cellular telephony over the past few years. And that's before it's even launched. The development of 3G started as far back as 1986 when the ITU started work on Future Public Land Mobile Telecommunications System (FPLMTS), which by 2000 had become known as International Mobile Telecommunications (IMT-2000). The aim of IMT-2000 was to provide a seamless global communications system for accessing packet-based multimedia content. The cellular section of the IMT-2000 scheme – which encompasses fixed networks, satellite

networks and a variety of wireless technologies – is the Universal Mobile Telephone Service (UMTS), otherwise known as 3G. Today, there are two leading contenders (and their derivatives like HSDPA, 1xEVD) from the competing 3G air-interface technologies ratified by the ITU, W-CDMA and cdma2000. The 3rd Generation Partnership Project (3GPP) is a collaboration agreement that was established in December 1998. The collaboration agreement brings together a number of regional telecommunications standards bodies such as ARIB, CCSA, ETSI, ATIS, TTA, and TTC.

Multiple antenna technology is proving to be an important technology consideration when designing next-generation voice and/or data wireless communication systems as well as when re-engineering existing systems to obtain higher bandwidths and capabilities. Multiple antenna communications is a technique of sending and receiving wireless signals, allowing more data to be transmitted without increasing bandwidth. This is accomplished by communicating along parallel spatial channels at the same time and in the same frequency. The standardization activities in each of the three BW markets highlighted above are considering various forms of multiple antenna applications for future releases.

While the concept of multiple antenna communication has been proven through theoretical and simulation-based studies, the real challenge has been turning this concept into a reality. Integrating multiple antenna technology into existing BW platforms efficiently and cost effectively and within a reasonable power budget represents a major technology challenge. In addition, the structure of the BW industry imposes its own constraints on large-scale adoption of multiple antenna technology for next generation BW networks. Understanding the interaction of the various market forces that will shape the future of next generation BW networks is the major motivation of this study. For our research, we identified a diverse group of individuals active in shaping the future of the BW industry. Candid interviews with these individuals provided us with their insight into market activity by region and market segments, customer requirements, strategies, and vision. Analyzing the responses of this diverse group led us to our primary conclusion that multiple antenna technology commercialization efforts should be aimed at demonstrating implementations of this technology in real world systems, and establishing a profitable cost-benefit trade-off both for equipment vendors and for service providers.

The rest of this paper is organized as follows. In Section 2 we discuss some of the requirements of next generation BW services and highlight how multiple antenna technology addresses these requirements. In Section 3 we present our research methodology and discuss the main results of our study in Section 4. Finally, in Section 5, based on our results, we formulate a commercialization strategy for multiple antenna technology. Conclusions are drawn in Section 6.

2. Assessing BW Requirements and Technology Offerings

In a successful BW service offering, customer demand will drive capacity requirements and demands for scalability. As a network operator's customer base grows, the BW solution should scale easily with the addition of new cells. The architecture of the BW offering should be based upon modular sub-systems to enable a ``success-based'' incremental capital model; that is, network operators can initially roll out service with a low-cost minimal configuration then easily, and non-disruptively, ``plug in'' capacity as subscriber growth dictates. In this way, incremental capital expense for capacity growth tracks with incremental revenues from subscriber growth.

Wireless links face significant attenuation from rain, foliage and blocking by outdoor terrain features or from furniture, people and penetration through walls in indoor environments. BW networks should provide better than 90% coverage reliability to subscribers in the service area despite these problems. A cellular architecture evolves from the system's ability to operate under Non-Line-of-Sight (Non-LOS) conditions. A fundamental characteristic of all Non-LOS channels is signal fading caused by the multiple reflections off objects in the environment. These, multiple reflections are also known as multipath. In order to operate under Non-LOS conditions, a system must provide many orders of *diversity*, or redundancy in the transmitted signal, such that the fading phenomena is successfully overcome. Further, significant investments have been made in existing PCS/cellular infrastructure. An outdoor BW deployment should maximally reuse such infrastructure for instance by co-locating antennas and cell-sites with PCS infrastructure.

To help network operators contain customer acquisition costs, the BW offering should be designed to support a subscriber self-install service model. This will eliminate many of the significant shortcomings that have plagued earlier systems; and in doing so, clears the way for mass deployment of BW services worldwide.

Propagation attenuation is a fundamental characteristic of all wireless systems, i.e. the received signal strength decays with increased distance of propagation. Since the data rate that can be supported over a wireless link is directly proportional to the received signal strength (fundamentally related by Shannon's capacity formula), the data rate decays with increased separation between the transmitter and receiver. Thus, supporting high data rates over large distances is a fundamental problem for wide-area wireless systems.

The following list summarizes important service and system performance capabilities of a successful BW offering

- Scalability through cellular (indoor or outdoor) deployment
- Non-LOS operation
- Compatibility with existing tower infrastructure (if outdoor deployment)
- Self-installable customer premises equipment
- User experienced data rates should exceed 0.5 Mbps.

Multiple antenna technology exploits multiple antennas at either/or the transmit and receive end with associated signal processing to enhance the performance of wireless systems in terms of capacity, coverage and throughput. In order to get high data rates or increased reliability of the transmitted signal, a user must be able to get a clean and strong signal from the transmitter. There are various way to increase the strength of the signal: using arrays of antennas at the transmitter that double or triple the strength of the signal seen by the receiver, using multiple antennas to listen to the different signals bouncing off of structures in the environment and using digital signal processing to re-construct a better signal, using the multiple reflected versions of the signal to better safeguard against unwanted interference or using multiple antennas to transmit double or triple the quantity of data. More formally, multiple antenna techniques[1] offer the following advantages [4], [5]

- Array Gain
  Multiple antennas coherently combine the signal energy improving the carrier-to-noise ratio. Array gain results in increased range of communication between the transmitter and receiver.

- Diversity Gain
  Spatial diversity obtained from multiple antennas, because the same transmission experiences multiple independent channel conditions, helps combat channel fading and improve performance particularly in Non-LOS conditions.

- Interference Suppression Gain
  Signals received at the multiple antenna elements can be adaptively combined to selectively cancel or avoid interference and pass the desired signal. This results in improved performance with cellular frequency reuse.

- Spatial Multiplexing Gain
  Spatial multiplexing uses multiple antennas at both ends to create multiple parallel data channels and improves spectrum efficiency (bps/Hz).

These advantages can translate into improved capacity (large number of users per square mile), coverage (higher penetration of service area) and throughput (high user bit rates) in BW networks.

While multiple antennas may seem favorable as a technology solution of choice in satisfying the needs of future BW systems, there are other competing technologies. For example, robust frequency diversity may be achieved through the use of a coded orthogonal frequency division multiplexing (OFDM) solution that combines bit-level interleaving, and forward error-correction. OFDM has other advantages too, no channel equalization is required in channels with heavy multipath. It is for these reasons that OFDM modulation is already a part of both IEEE 802.11 and IEEE 802.16 standards. Also, higher data rates may be achieved by increasing the allocated bandwidth. For instance IEEE 802.11 has a bandwidth allocation that is 4 times the 3G allocation and IEEE 802.16 supports variable bandwidth allocation. Interference mitigation techniques are well known in the technical literature to combat co-channel interference. Thus, while viable technology alternatives are available in principle, the debate on a single converged technology offering for future BW is still active.

3. Research Methodology

We identified about a dozen primary points of contact (PPOC) from industry (both established companies as well as start-ups), venture capital firms, academia and are seeking to collect their responses to our questions. These PPOCs represent our primary source of data and represent a good diversity of perspective across the wireless industry. All the PPOCs we

[1] We interchangeably use the phrase ``multiple antenna technology'' and the more common acronym ``MIMO'' which stands for ``multiple-in multiple-out'', to describe both the physical system that has multiple transmitting and receiving antenna elements and the associated signal processing.

spoke with represent companies that are active participants in the relevant standards organizations.

The survey took place from December 2004 to February 2005 and involved discussion with engineering managers, marketing managers, technologists and academics at all organizational levels. Most PPOCs have been willing to provide us with their insight of market activity by regions and market segments, customer requirements, strategies, and vision openly. While the subject matter is inherently, at times confidential or proprietary, we focused on trends and publicly stated vision statements. All material presented in this paper has been shared with each of our PPOCs. To understand the nature of our discussions, we list a typical set of questions that were posed to the selected PPOCs. Our discussions, however, were not limited to these questions.

- What does your company see as the future of wireless broadband services?

- Please identify your responsibility in the context of your company's vision for providing chipsets/infrastructure/services for next generation wireless broadband?

- What does your company envision as being the main technology enabler to meet the requirements of future wireless broadband services?

- How much investment does your company have (or plan) towards deploying infrastructure for next generation broadband wireless services?

- Where do you see multiple antenna technology (or MIMO) in satisfying the requirements for next generation broadband wireless services?

- What challenges or (alternative technologies) do you see for multiple antenna technology being part of next generation broadband wireless systems?

- Is there a perceived cost increase associated with implementing MIMO technology, how much cost differential do you foresee, is that increased cost justified given the increase in
- capacity/robustness that MIMO purports to provide?

- Which MIMO-focused company (other than your company) do you see as a leader in the area?

The primary objective of this question set was to initiate a dialogue with the PPOC and steer the discussion about the PPOCs perception of multiple antenna technology towards satisfying the needs of next generation of BW services.

4. Responses: A Sampling of Multiple Antenna Technology ``High-points''

Since this study was performed as an ``assessment'' of the perception of current and future multiple antenna technology, and since its conduct involved numerous perspectives gathered from a variety of companies, it is appropriate to list and explain the dominant points of discussion that we observed, and highlight challenges that we faced.

Enormous financial stakes in the future of the wireless industry have created a very intense competitive environment among many wireless ``players''. In turn, this has diminished the willingness to share not only current research and development plans but also longer-term plans among companies. A related realization that the rapidity with which the wireless technology is used in a variety of new applications, has created an environment in which confusion (if not chaos) is common. Not only the general public but also the technology developers themselves lack a firm, commonly held vision as to what is important (both in terms of products as well as in terms of services). Consequently, we had to use our own expertise and understanding of the field to interpret and complement the inputs we received.

Coexistence of IEEE 802.11 based local-area broadband access with wide-area connectivity being complemented by alternatives based on 3G derivatives like HDR and HSDPA in the short term is a common vision shared by all PPOCs. The laws of wireless propagation preclude wide-area connectivity at broadband data rates. Emerging standards like IEEE 802.16 will likely serve to enhance the capabilities of wide-area access offered by 3G derivatives, even though at present they are viewed as competing technologies.

Although the theory of multiple antenna transmission is quite mature by now, concerns about cost and implementation have held back the incorporation of these advanced methods in actual systems. In general multiple antenna technology is yet to fulfill its promise. There seem to be many undiscussed issues in the technical literature with respect to antenna design, and implementation of joint hardware and software systems design that can exploit the multiple antenna capability. For example most multiple antenna work does not address multi-cellular deployment where there is interference from neighboring cells which effects robustness of multiple antenna techniques.

Multiple RF chains required for multiple antenna operation are expensive up front: approximately 30% on the client side BoM. Physically, mounting multiple antennas on the client side require physical space, increased power consumption and consequently reduced battery life. Further, the advantages of multiple antennas accrue when there is sufficient physical spacing between the multiple antenna elements. For hand-held devices, this sufficient separation may not be available because of small form-factor constraints. Even at the infrastructure side, multiple antennas mean lots of operational headache. From cabling to setting up antenna panels on the towers, ensuring the towers can handle the extra weight of the cables and antennas. An important difference between licensed and unlicensed spectrum is that [multiple antenna equipped] devices designed for operation in the licensed spectrum will tend to be more expensive than the unlicensed counterparts because of more stringent FCC regulation which requires sharper front end RF filters. Further, any investment in the [expensive] licensed spectrum will make the carrier use that spectrum more efficiently and this is where multiple antenna technology comes in naturally. Because of this reason technologies that increase spectral efficiency are natural candidates for licensed spectrum.

Regardless of the increased device costs with multiple antenna technology, to analyze the equation completely, the increase in capacity (and hence increase in number of users you can support) must be balanced against the cost differential per user. In other words, the incremental hardware cost must be amortized over the increased number of users. This analysis is not easy because of the variables involved, but needs to be done.

We were surprised by some of the carriers' concern about hardware cost. Typically, the equipment vendor is more cost sensitive than the carrier. The carriers should be in a driving position here: they should lay down strict requirements (i.e. strict performance criterion) for the next generation multiple antenna enabled systems and dictate the cost structure they are comfortable with. For example, the CDG (CDMA Development Group) which was primarily led by carriers/operators helped define the capabilities of the next generation 3G standard. The carriers' inability or unwillingness to dictate terms in this regard is at the very least a sign of them not being convinced on the true benefits of multiple antenna technology in the context of the next generation of broadband wireless services.

Multiple antennas may make more sense with emerging standards like IEEE 802.16 or IEEE 802.11, which are emerging standards with no serious investment or infrastructure (compared to PCS). As soon as a technology impacts standards, there is a significant cost/inertia associated with it. Especially if the standard happens to be cellular. In this regard, IEEE 802.11 provides a unique opportunity. By all measures, the emerging next generation WLAN standard, IEEE 802.11n, is a ``light-weight'' standard. It operates in the unlicensed spectrum and the specification of the air interface is limited to the PHY and MAC layers, i.e. does not require significant investment towards defining network operation.

Multiple antenna ``appliques'' for cellular systems – which attempt to provide multiple antenna capability without changing standards - are feasible but they require a break-in or visibility into the carrier/vendor hardware platforms, which is not easy. Further, any new technology that has a standards impact is frowned upon. To go through the approvals required during standardization is a techno-political process of extreme proportions. This appears to be a deterrent for start-ups or new ventures from breaking into an established playing arena dominated by traditionally risk-averse heavy-weights.

For the most part simpler multiple antenna techniques like receive side diversity may be rolled out first. Then, perhaps the vendors will start making firmware changes to exploit the multiple antennas in other ways, and that may eventually lead to true multiple antenna platforms. But in general, any changes to the existing equipment that is not limited to a firmware (or driver level code) upgrade is a tough change. Also, it is unclear how multiple antenna technology interacts with legacy devices. For example if there is a mix of multiple antenna equipped and legacy devices, what impact does that have on the benefit of multiple antenna algorithms?

Almost always simpler sub-optimal choices are preferred that are cheaper to implement. As an example, if additional capacity is required carriers would prefer first exhausting spare spectrum, plus there are other alternatives like cell splitting, and in the GSM/EDGE context single-antenna interference cancellation techniques that exploit GMSK modulation are being discussed in the appropriate standards organization. The short-term need for additional services may well be satisfied with HSDPA without going to multiple antenna technology.

5. Formulating A Commercialization Strategy for Multiple Antenna Technology

The greatest opportunity for large-scale commercialization and adoption of multiple antenna technology is in the context of local-area broadband wireless services.

5.1 WLAN Market for Multiple Antenna Technology

MIMO, already on the shelves in so-called Pre-N routers and adapters from Belkin [6], uses a number of antennas to send multiple signals as a way to significantly increase the speed and range of a wireless network. Among major chip-set providers, Airgo, Atheros and Broadcomm have announced products that use MIMO technology. Among major vendors, LinkSys, Dlink, Netgear and US Robotics have announced products based on these chip-sets.

Airgo recently reached a milestone [7] of shipping more than one million of its award-winning True MIMO chips in the first quarter of retail production. The rapid adoption of Airgo's True MIMO technology by retail OEMs such as Belkin and Linksys – which according to the Synergy Research Group represent over 30% of the market share for SOHO/home Wi-Fi equipment – reflects the consumer demand for a superior Wi-Fi experience and signifies the immediate impact that True MIMO has made.

Atheros' [8] IEEE 802.11 a/g chip-set uses phased array beamforming, cyclic delay diversity, and optimal receive combining to deliver higher performance even when the new chip-set is only on one end of a wireless connection. The new chip-set therefore enables breakthrough performance with maximum compatibility for the millions of Wi-Fi products in the market.

Linksys announced [9] its own products that use the same chips, manufactured by Airgo, that are in the Belkin products. The Wireless-G Router with SRX WRT54GX has an estimated street price of $200 while the Wireless-G Notebook Adapter with SRX has an estimated street price of $130. Both are available now.

Netgear announced [10] plans for products that it says take a sophisticated approach to improving range and speed. Products incorporating BeamFlex technology use seven internal antennas and dynamically change the way they beam Wi-Fi signals to work around obstacles and interference. The BeamFlex technology, developed by Video 54, will be included in Netgear's RangeMax products due out in March. The technology can be used with MIMO chips or with standard IEEE 802.11g chips.

D-Link announced [11] products using MIMO technology that incorporate beamforming and receive-combining technology. Its products will use chips from Atheros. That company claims its MIMO implementation is more compatible with existing IEEE 802.11g products and is faster than the Airgo chips, both in all-MIMO networks and in networks with a mixture of MIMO devices and other devices using IEEE 802.11g.

U.S. Robotics is taking a more conservative approach to extending range. With lots of corporate customers, U.S. Robotics not to market MIMO products that may not be compatible with the final IEEE 802.11n standard. Instead, the company is pursuing ways to make standard IEEE 802.11g products more powerful. U.S. Robotics' Max G line [12] will boost the power of the Wi-Fi signal by 25 percent and increase the maximum speed to 125 megabits per second. The combined effect is approximately a 50% increase in range. The MAX G product family is based on Broadcom's AirForce chipsets and is the first consumer product to feature Broadcom's BroadRange range-extension technology in addition to its 125 High Speed Mode throughput enhancement. And the Max G line will be less expensive than MIMO products. A router will sell for $80 and client adapters for $70.

5.2 Discussion

The interest that the WLAN market is expressing in MIMO technology is not co-incidental. The indoor environment, which WLAN deployments are customized for, provides a rich scattering physical environment - one in which MIMO thrives. Since the IEEE 802.11 standard is time-division duplexed, there is an inherent savings in hardware costs because each device requires a single set of RF hardware (used either for transmission or reception but not both simultaneously).

From a vendor perspective, it is the flexibility of MIMO technology to cater to different physical environments (for data rate, for robustness, for range) that provides the greatest room for product differentiation and competitive edge.

Further, with the proliferation of its predecessor IEEE 802.11b, the next generation WLAN standard IEEE 802.11n expects to build upon a large established customer base. It is in this context of next generation WLANs that MIMO technology has gained greatest acceptance. Versions of MIMO have been proposed in the IEEE 802.11n standards group and it is likely that many versions of MIMO will likely be at least optional components of the standard.

6. Conclusions

The following items stand out as the major areas (both technology and commercialization aspects) of future wireless technology that require significant additional research.

- Multiple antennas provide a dimension to increase system performance, differentiate between vendor products, can enable new services and markets. Vertical integration of protocols and systems design of these multiple antenna equipped future radio platforms is still a matter of much debate in the industry.

- While institutional (universities, commercial labs) research has focussed on the potential of multiple antenna technology, corresponding advances in implementation aspects of this technology has lagged. This has created a market that professes a cautious approach to adoption of this technology for infrastructure-heavy future wireless broadband systems.

These stood out as being dominant concerns of all companies we spoke with. Based on this study, our primary conclusion is that multiple antenna technology commercialization efforts should be aimed at demonstrating implementations of this technology in real world systems, and establish a profitable cost-benefit tradeoff both for equipment vendors and for service providers.

In terms of the three market segments we identified for our study, we conclude by observing that MIMO technology is most suited to the WLAN segment for a variety of reasons that range from technical to the cost structure of the established infrastructure- and investment-heavy sectors like cellular/PCS. Our results indicate that the WLAN segment is most ``receptive'' to the promise of MIMO technology and presents the biggest avenue for innovation and technology commercialization. However, given that there are already multiple antenna WLAN products in the market, it is perhaps too late for new start-up ventures to capitalize on application of multiple antennas to WLANs. Perhaps a technology licensing model where research groups partner with industry for research focussed on the practical and hitherto undiscussed aspects of multiple antenna technology is a valid model.

Fixed wireless opportunities exist, but most vendors or service providers in the space are still trying to demonstrate a return on investment on their first generation products in order to survive to the day where they may consider multiple antenna technology. Even in the emerging 802.16 d/e space multiple antenna technology is perceived as a future ``nice-to-have" than a near term ``must-have" feature.

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