Future Trends in Commercial Wireless Communications and Why They Matter to the Military

Julia Andrusenko, Jack L. Burbank, and Feng Ouyang

ABSTRACT

The rapid evolution of commercial wireless communications technology has resulted in capabilities that far surpass their military counterparts in many ways. Thus, the military community is increasingly interested in leveraging commercial technologies and techniques to address its communications needs. In fact, one need look only at today's trends in the commercial domain to understand tomorrow's military solutions (and their challenges and limitations). Because of this reality, the Johns Hopkins University Applied Physics Laboratory (APL) is dedicated to maintaining mastery of commercial technologies and involvement with the commercial wireless standards communities. By maintaining this expertise, APL can leverage these technologies and solutions to meet sponsor needs in affordable and effective ways and can also understand and manage the risks and limitations of these technologies. By actively participating in the standards bodies, APL experts believe they can help tailor these technologies to better meet sponsor needs. This article provides a brief overview of the evolution of commercial wireless broadband communications. It also examines some of the key wireless technology trends that will likely drive the development of the next generation of wireless solutions and affect the military solutions of tomorrow.

INTRODUCTION

The ways people and devices connect to the Internet have changed significantly in recent years. Numerous highly capable wireless networking technologies have been developed and widely deployed. Today's commercial wireless communications landscape is fueling a revolution in the way people access and share information as the "wireless Internet" continues to take form. Users are embracing these new capabilities and are demanding additional capabilities to satisfy their needs. This symbiotic relationship is creating a startling evolution in wireless networking capabilities in the commercial domain. It is still surprising how wireless technologies have become so integrated in our daily lives, even in the remotest parts of the world. Cell phones, tablets, laptops, smart TVs, and other devices provide a level of connectivity to the world and media content that we could not have imagined in the recent past. This trend continues to accelerate, making it difficult to imagine the type of wireless society we might find in 20 years. It is not surprising that the military community would want to leverage this rapidly growing capability to address its own communications needs. The Johns Hopkins University Applied Physics Laboratory (APL) recognizes the power of commercial technologies and approaches and attempts to leverage them to provide affordable and effective solutions for its sponsors. This article discusses the relationship between the commercial and military domains, some of the key factors driving commercial development, some of the key technology trends in the commercial communications landscape, and APL's role in this space.

INCREASING MILITARY RELIANCE ON COMMERCIAL WIRELESS TECHNOLOGIES: PARADIGM SHIFT

Military wireless communications systems have historically been based on proprietary technologies that have been designed to meet a stringent set of performance requirements. These systems are often designed to operate in highly disadvantaged environments where equipment will be exposed to harsh environmental elements such as sand, dust, dirt, and water, as well as extreme temperature variations. These wireless communications systems also have historically been designed to provide extreme levels of security to protect data that may be sensitive to national security, tactical operations, or strategic goals. This security requirement includes not only protecting information in transit through wireless networks but also protecting the wireless devices themselves, as they may operate in scenarios in which they are prone to capture. Indeed, the military domain faces many challenges that are more stringent than those in the commercial domain.

With all that said, however, there has been a growing trend over the past 25 years for the increasing use of commercial technologies, techniques, and equipment to solve problems in the military wireless communications domain. This is due to multiple factors. During the Cold War era, it was common for military technology to be ahead of technology in the commercial sector, with military technologies often advancing the state of the art. However, with reductions in military spending and research and development since the Cold War era, the military community sometimes lags the state of the art. In many cases, military networks are often based on technology from the 1970s or 1980s. Today it is common for the commercial domain, through its enormous advantage of economy of scale, to advance the state of the art in wireless communications. Consequently, interest in and use of commercial technologies has been steadily increasing within the DoD community for decades.

This trend was bolstered in 1994 by The Perry Initiative. Instituted by William Perry, U.S. secretary of defense from 1994 to 1997, this 1994 DoD memorandum mandated a heavier reliance on commercial-off-the-shelf (COTS) technologies to solve DoD communications needs. Then, in 1996, the Defense Advanced Research Projects Agency (DARPA) requested a 1-year study on wireless communications to be conducted by the Computer Science and Telecommunications Board of the

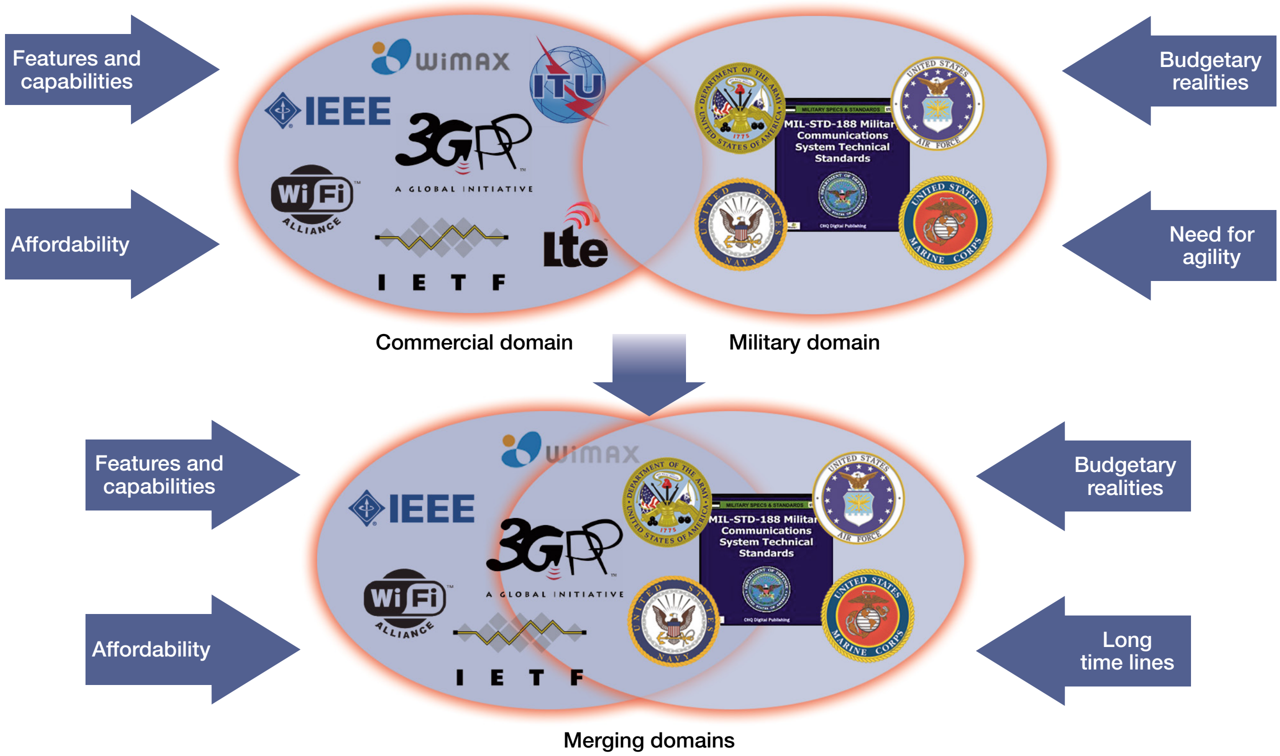

Figure 1. Various forcing functions that are pushing together the commercial and military wireless communication domains.

National Research Council. The Computer Science and Telecommunications Board subsequently created and tasked the Committee on Evolution of Untethered Communications to advise DARPA on the relationship between the military and commercial wireless communications communities. The resulting report predicted that the market forces of the commercial domain would result in technologies that would largely fill perceived gaps in military wireless communications needs, while noting several military-unique challenges that the commercial domain would likely never solve. A thorough treatment of the history of COTS technology use in the military domain can be found in Ref. 1.

Today the influence and impact of commercial wireless networking technologies can be seen pervasively across the DoD landscape. This pervasiveness includes the adoption and use of not only COTS equipment but also military-specific equipment that has been influenced by or incorporated commercial technologies. And this trend is growing. There are many reasons for this trend (in fact, too many to list here). Many of these reasons are debatable, but there are some undeniable factors actively driving the military community to adopt commercial solutions. These factors are listed below and are also depicted in Fig. 1:

- **Cost:** Military-specific equipment is costly. Commercial equipment is inexpensive. With modern budgetary realities, cost is a strong forcing function.
- **Life cycle:** The military domain has changed significantly over the past decade. Large-scale troop deployments are on the decline, while small-scale specialized force deployments are on the rise. Large-scale conventional war has been largely replaced with asymmetric warfare. Adversaries are typically asymmetric threats who are far more agile than large nation-state players of previous decades. The changing world requires faster adaptation and anticipation, which subsequently requires acquisition cycles that are fast and agile. Commercial technologies are more suitable for this model than specialized military-specific solutions.
- **Feature set:** In many cases, compared with their military counterparts, commercial technologies are superior in almost every aspect of performance.

Widespread adoption of commercial technologies would seem to enable the “better, faster, cheaper” paradigm. However, it is important to note, as did the DARPA-commissioned study in 1996, there are several military-specific performance requirements that will likely never be fully met by the commercial domain. For example, the commercial domain will likely never require the same types of security or environmental survivability required by the military domain. Consequently, even as commercial technologies are widely adopted by the military, there will likely remain a need to create military-specific variations of those technologies to fill the gaps left by the commercial sector.

THE COMMERCIAL WIRELESS COMMUNICATIONS DOMAIN — A SIMPLISTIC VIEW

The landscape of existing wireless standards is vast and diverse, as can be seen in Fig. 2. Although Fig. 2 provides a relatively accurate representation of the aforementioned wireless landscape, it is highly simplistic in nature. It attempts to convey that, ultimately, there is no one superior technology. All wireless technologies—past, present, and future—have strengths and weaknesses because each technology has been (and will be) developed to solve a particular problem. A technology may work well for one application but suffer in another application. There is no one-size-fits-all technological solution to address all problems. This is an important realization—a technological solution developed to solve a commercial problem may have serious limitations when applied to the military problem space. Therein lies the challenge in adopting commercial technologies for military applications. Maintaining an intimate knowledge and understanding of commercial technologies, not just

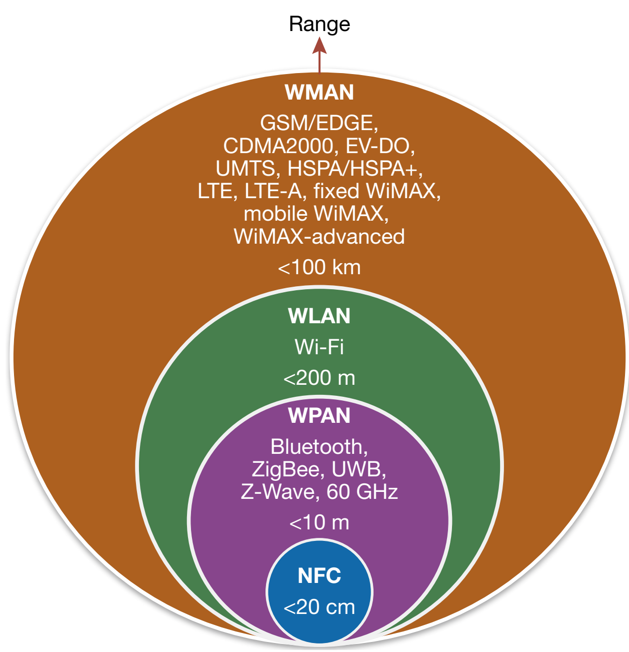

Figure 2. Landscape of wireless technologies. EDGE, enhanced data rates for GSM evolution; EV-DO, enhanced voice-data only (optimized); HSPA, high-speed packet access; NFC, near-field communications; UMTS, universal mobile telecommunications system; UWB, ultra-wideband; WiMAX, worldwide interoperability for microwave access; WLAN, wireless local area network; WMAN, wireless metropolitan area network; WPAN, wireless personal area network.

what they are but also why they are, is key to successfully using them in military solutions that are affordable and also effective.

WHAT DRIVES COMMERCIAL WIRELESS TECHNOLOGY DEVELOPMENT?

It is common to hear statements such as "spectrum is a limited resource" and "there is a worldwide spectrum shortage." RF spectrum is indeed a limited resource. Although new portions of RF spectrum (e.g., 60 GHz) are beginning to see increased interest, "convenient" RF spectrum (i.e., spectrum that is desirable in terms of propagation and cost) is not readily available. This shortage is due to increasing demands and inefficient usage. Because of this shortage, there is still a strong, vibrant research community relentlessly searching for more efficient ways to use spectrum.

There is no getting around the physics of the problem. The only way to provide an increased data rate for a given communications channel is to either improve bandwidth efficiency or increase bandwidth. This reality has led to the need for improved modulation techniques, more efficient media access control designs, and fundamentally new approaches to old problems. Claude Shannon set the bar more than 60 years ago, but clever scientists have found ways around Shannon's bandwidth efficiency limits by redefining what a channel means. In the era of analog communications, we defined a channel in terms of frequency. As we ushered in the digital era, we began to also think of a channel in terms of time (e.g., time slots). But over time, we found other fundamental aspects of a signal that we can manipulate to redefine a channel. We next discovered how to further define a channel in terms of power [e.g., code-division multiple access (CDMA)]. Then we discovered how to further define a channel in terms of space [e.g., multiple-input multiple-output (MIMO)]. No one has proven Shannon wrong, nor is anyone likely to ever do so. We are simply discovering new ways to define the inputs into Shannon's arguments. As a result, amazing bandwidth efficiency advancements have been realized and widely deployed over the past several decades. However, bandwidth efficiency improvements alone have not proven sufficient to keep up with user demands. This lag leads to the need for spectrum.

The factor driving increased need for spectrum is the user's need for more data—the need for increased capacity to meet user demands. The smartphone and tablet revolution has fueled an insatiable appetite for bandwidth. Technology developers are struggling to keep up, often being asked to provide more data with no additional, or even less, physical resources. Devices must consume less power because consumers will not tolerate poor battery performance. Devices must be smaller and lighter because consumers will not tolerate bulky devices. Efficiency must improve, in terms of power, size, and bandwidth consumption.

Beyond the enduring need for improved efficiency, there are two key technology developments, neither of which is particularly unique to wireless, that are expected to continue to fuel the advancement of wireless technologies for the foreseeable future: cloud computing and the Internet of Things (IoT).

Cloud Computing

Cloud computing has become a disruptive technology over the past 5 years, and it is expected to continue to be highly disruptive into the foreseeable future. However, the term *cloud computing* has often been misused and more often misunderstood. Cloud computing refers to a network model in which applications reside on network servers and are accessed from end clients (sometimes with decreased capability) instead of residing on end client devices such as PCs, laptops, or smartphones. Decreased-capability end clients that rely on the cloud computing model are often referred to as thin clients or zero clients, depending on the amount of their reliance on the cloud. In many ways, cloud computing is equivalent to the old mainframe-terminal model of 40 years ago. However, one key difference is that cloud computing typically relies heavily on the concept of virtualization, where servers may actually be virtual appliances and an actual physical device may be hosting many virtual appliances. To end users, it may appear as if they are accessing a physical server, but in reality they are accessing a piece of software that is emulating a physical server. This concept of virtualization allows for significant network abstraction and rapid reconfiguration to meet user needs.

Cloud computing has also extended into the realm of media distribution. Instead of holding media such as music and movies on end client devices, end users are increasingly storing media and other content in the cloud, accessing it remotely as necessary. Thus, online storage is one of the most significant uses of cloud computing.

Although cloud computing is an incredibly powerful concept for information technology professionals, network designers, and content providers, this trend has placed enormous strain on the communications infrastructure. With end users increasingly accessing both applications and content from the cloud, their bandwidth consumption has significantly increased. Cloud computing is expected to increase, and combined with increasing user mobility and mobile computing, this trend will continue to place strain on wireless communications infrastructure. Cloud computing is one of the main reasons we expect the time frame between major commercial technology releases to continue to shorten. This shortened release schedule is already starting to be realized. Ten years ago, major commercial wireless deployments happened every 5–10 years. In modern times, major wireless technology rollouts happen every 2–3 years. This shorter release schedule crosses all wireless sectors, including both the cellular industry and the traditional data networking community (e.g., Wi-Fi).

The IoT

The term *Internet of Things* (IoT) is shrouded in mystery and confusion and represents different things to different people. The most common view of the IoT refers to the pervasive inclusion of Internet connectivity, typically wireless connectivity, in common everyday objects. In the IoT paradigm, Internet connectivity extends beyond traditional devices such as laptops and smartphones to include everyday items such as refrigerators, microwave ovens, dishwashers, thermostats, automobiles, and road signs. Missing in this common definition are micro-electromechanical (MEMS) systems. MEMS are embedded into objects to enable communication and interaction with the environment. These objects can range from humans with implanted medical devices to controllers in oil refineries. Regardless of exact definition of the IoT, all current projections estimate tens of billions of devices will be connected to the Internet by 2020, and wireless technology will be a key enabler in realizing this IoT vision.

Connected IoT devices can generate data and information that can be accessed from anywhere via the Internet. This connectivity allows governments, businesses, and individuals to make data-driven decisions in real time. The military can leverage this type of pervasive environment to meet today's mission of information dominance in the cyber and physical battlefields. The IoT paradigm is expected to be brought to bear within the DoD community as it is highly aligned with numerous military operational needs. And as this paradigm is increasingly realized, wireless communications technologies are expected to rapidly evolve to meet the these new challenging needs.

Spectrum

As already mentioned, spectrum is a precious resource, and there is simply not enough to meet the needs of today's user base, much less the needs of the users of tomorrow. This problem is exacerbated by the outdated way we manage spectrum. Regulatory agencies allocate spectrum for particular types of services and that spectrum is then licensed to bidders for a fee. These allocations and licenses are static in nature, which means that the designated spectrum is unavailable for use, even if those who own the rights to that spectrum do not use it. This model has led to considerable inefficiency in spectrum use and has sometimes created an unnecessary shortage of spectrum.

To lessen the burden on wireless networks operating in licensed spectrum, emphasis is increasingly placed on technologies (usually short range and low power) that operate in unlicensed spectrum such as TV white space, Wi-Fi, personal area networks (e.g., Bluetooth and ZigBee), ultra wideband, 60-GHz, and near-field communications devices. These technologies are increasingly used to offload services that would have historically used licensed spectrum and to improve overall network capacity. It is expected that the commercial domain will continue to find novel methods and develop new technologies to continue using unlicensed spectrum, which will profoundly impact the technologies available to the future military community.

Spectrum shortage has also led to significant global harmonization and spectrum reclamation efforts by commercial advocacy groups. Harmonization refers to the concept of making the same spectrum available for the same application in all world markets. The argument raised to various spectrum regulatory authorities is that harmonization can enable economic gains because devices can be more affordably produced for globalized markets. There has been significant progress in this regard, with many regions of the world beginning to allocate spectrum in a manner consistent with other regions of the world. It is believed that this trend will continue and that increasingly there will be global spectrum bands of operation for certain types of wireless devices. This standardization will have profound effects on future military solutions—it will influence future technology availability as well as how this technology can be effectively used globally.

Spectrum reclamation is also an important topic that will affect future wireless military systems. It refers to the process of reallocation of spectrum on the basis of perceived need. Many arguments have been made that the manner in which spectrum has been allocated and regulated does not align with the needs of the modern world. Many reclamation efforts have been successful. Significant amounts of spectrum have been taken away from certain communities and instead made available for mobile wireless network applications. An example is the reallocation of portions of the UHF band from commercial television broadcasters to mobile network service operators. Experts believe that this trend will continue and that increasing amounts of spectrum will be made available to commercial mobile wireless networks with reallocations from other commercial sectors and government and military applications. Although this reallocation is an ongoing and dynamic process, it has sparked the desire for new technology and adoption in a wide variety of sectors, both commercial and military. In many cases, it has been a contributing factor in the military's and the government's increasing reliance on commercial solutions.

EVOLUTION OF WIRELESS BROADBAND COMMUNICATIONS

Cellular technologies have evolved at an astounding rate over the past 10–15 years not only in terms of their deployment and usage but also in terms of their capabilities. A little over a decade ago 2G technologies such as global system for mobile communications (GSM) and Interim Standard 95 (CDMA) were the state of the art in cellular communications. As recently as 1992, GSM had not yet been deployed outside of Europe. Today, GSM spans the globe with more than 6 billion subscribers. A decade ago, most cellular networks provided data capabilities comparable to those of dial-up modems. The past decade has seen multiple generations of technology development, deployment, and adoption that have provided several orders of magnitude of improvement in data rates and general capabilities. Technologies such as universal mobile telecommunications system, wideband CDMA, high-speed packet access, CDMA2000, CDMA2000 evolution-data optimized, and long-term evolution (LTE) have catapulted cellular networks into the forefront of the data revolution and sparked the rise of the wireless Internet. To put this all into perspective, over the course of a decade, cellular data networks have transformed from the equivalent of a dial-up modem to that of a fast Ethernet connection. Figure 3 depicts the evolution of cellular communications over the past 15 years.

The cellular industry was long marked by competing technologies that fragmented the global market into a CDMA world and a GSM world. A key takeaway from Fig. 3 is that these two worlds are merging together into a single global technology path; all viable technology paths now lead to LTE. Over time, the entire global market will increasingly converge onto the same technology, which will likely enable an entirely new breed of global mobile devices. In fact, in the long-term view, the only differentiating factor between countries and markets may be frequency bands of operation. It should be noted that this discussion does ignore worldwide interoperability for microwave access (WiMAX) and its role in the commercial wireless landscape. WiMAX has been endorsed as a 4G technology. Although its future is uncertain, the authors believe that WiMAX is more likely to assume niche roles in the commercial wireless landscape, with LTE remaining the dominant cellular technology of tomorrow. This will give LTE a significant advantage in the long term in terms of economies of scale and vendor diversity, which will make it, and its descendent technologies, an increasingly attractive option for the military community.

KEY WIRELESS TECHNOLOGY TRENDS

Many of the most important commercial wireless technologies share key technological similarities, as will likely future commercial wireless technologies. There are several key technology trends that are likely to affect the development of the next generation of commercial wireless standards and, subsequently, future military solutions; these trends include MIMO, multi-carrier modulation, cognitive radio, and network coding. However, a full treatment of all these trends is beyond the scope of this article. The remainder of this article focuses on MIMO trends in the commercial domain.

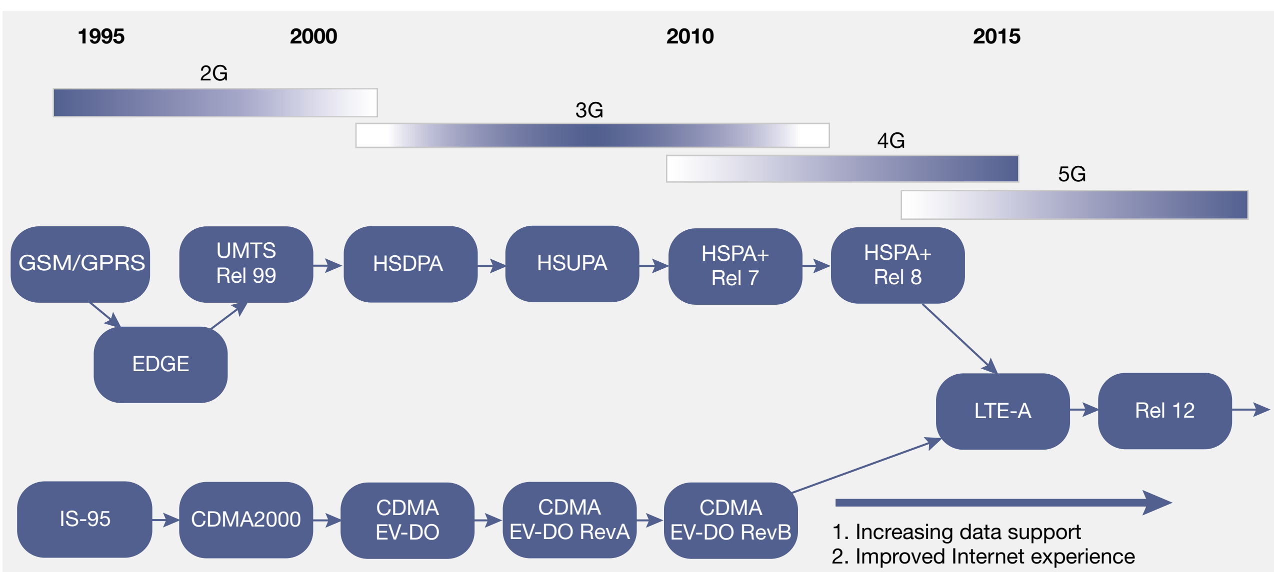

Figure 3. The evolution of wireless broadband communications. EDGE, enhanced data rates for GSM evolution; EV-DO, enhanced voice-data only (optimized); GPRS, general packet radio service; HSDPA, high-speed downlink packet access; HSPA, high-speed packet access; HSUPA, high-speed uplink packet access; IS-95, Interim Standard 95; UMTS, universal mobile telecommunications system.

MIMO Technologies in Commercial Systems

MIMO is a modern wireless communications technology that uses multiple antennas on one or both ends of a communications link. With multiple antennas, spatial characteristics of the radio transmission can be controlled and manipulated to improve the performance of the wireless link. Although the concept and theories of MIMO were developed in the 1990s, commercial products using MIMO technologies first began appearing in the market around 2003.

There are two ways a MIMO system can provide better performance in wireless communications under certain channel conditions. One is providing a higher data rate under a given channel. The other is providing a more reliable communications link under channel fading.

The first technique is referred to as spatial multiplexing (SM). Using multiple antennas on both transmit and receive sides and with a scattering-rich channel, multiple spatial channels are generated to support parallel transmission of multiple data streams. This technique results in a higher data rate under comparable signal-to-noise ratio conditions. SM can be performed with and without knowledge of the channel state at the transmitter (i.e., closed loop and open loop).

The second technique also takes advantage of the multiple spatial channels. However, the same data are transmitted over these channels. This technique provides diversity against channel fading, yielding higher transmission reliability in mobile communications scenarios. This is referred to as spatial diversity. A special coding technique, referred to as space-time block coding, is used so that the receiver can receive and combine the data with only one antenna. With space-time block coding, different versions of the same data are transmitted using multiple antennas and multiple time slots. In many practical systems, instead of using multiple time slots, multiple orthogonal frequency-division multiplexing subcarriers are used. Such a scheme is thus called space-frequency block coding.

In addition, another embodiment of MIMO technology is beamforming. Similar to antenna array techniques, beamforming focuses the radiation energy onto the receiver, improving signal quality. It also reduces interference to other users, enabling more simultaneous radio links at the same frequency. The receiver can operate in the conventional single-antenna mode in receiving operations. However, the protocol design needs to enable the transmitter to obtain channel state information.

MIMO Implementations in Current Commercial Wireless Systems

Shortly after its inception, MIMO technology was embraced by the wireless communications industry. In addition to proprietary MIMO-based systems, various wireless standards bodies quickly worked to adopt MIMO technologies.

Single-User MIMO Technologies

Single-user MIMO refers to the basic MIMO technologies described earlier. It pertains to a point-to-point wireless link. There is no interaction between multiple wireless links.

Table 1 summarizes some of the commercial wireless technologies that support single-user MIMO operations along with the number of data streams supported (the SM column in Table 1). Although there are some differences in details and supporting protocols across these technologies, the basic capabilities are similar.

Multi-User MIMO

Multi-user MIMO (MU-MIMO) refers to the technology with which multiple users share the same time and frequency in transmission using MIMO technologies. Some simple forms of MU-MIMO are already in use.

For example, LTE allows a base station to generate two beams optimized for two receivers. A mobile receiver can decode its own beam with a low level of interference from the other beam. Such interference can be further reduced by smart scheduling in choosing the user pairs that are well separated in space channels. LTE-advanced (LTE-A) increases such capacity to support up to four users. 802.11ac provides a similar capacity, where up to four data streams can be sent to up to four receivers (up to eight total streams) while each receiver can receive single or multiple data streams. This type of MU-MIMO is actually a special case of SM with transmit-side channel state information. The transmitter can manipulate the signals to minimize mutual interference.

MU-MIMO can be used for receiving, as well. In this case, a base station can simultaneously receive from multiple users while removing mutual interference through receiver beamforming and multi-user detection (MUD).

Table 1. MIMO technologies in various wireless standards

Standard	SM	SD (SFBC/ STBC)	BF
3G cellular	2 DL		
LTE	4 DL	DL	DL
LTE-A	8 DL, 4 UL	DL	DL
WiMAX	8 DL, 4 UL	DL	
802.11n	4	Yes	Yes
802.11ac	8	Yes	Yes

BF, beamforming; DL, downlink; SD, spatial diversity; SFBC, space-frequency block coding; STBC, space-time block coding; UL, uplink. The numbers in the SM column are the maximum numbers of data streams supported.

Emerging MIMO Technologies

MIMO technology is still an active research area. New inventions and discoveries continue to be fueled by the need for increased capacity. This section discusses a few research efforts that have clear and significant application potentials for the commercial and military domains.

Distributed and Cooperative MIMO

Closely networked nodes can jointly transmit and receive signals, effectively serving as multiple antennas of a MIMO transmitter or receiver. Such configuration is referred to as distributed MIMO, cooperative MIMO, or virtual MIMO. Because the antennas are much farther apart in this case, the effective channels are more scattering rich and uncorrelated, providing higher capacity bounds. On the other hand, as limited by the interconnection among the cooperating nodes, the levels of joint operations and synchronization are not the same as those for a traditional MIMO transceiver.

For example, LTE-A supports coordinated multi-point, which helps users at the cell edges by transmitting and receiving signals through multiple base stations. Coordinated multi-point is actually a set of still-developing technologies. Currently, joint signal processing among base stations for jointly transmitting to and receiving from a mobile user is a main component of coordinated multi-point. It also includes joint scheduling among neighboring base stations in resource allocation and beam-forming strategies so that users with the least level of mutual interference can be chosen to share the frequency-time block.

Other than commercial wireless networks, distributed MIMO in sensor networks is also being actively researched (e.g., Ref. 2).

Massive MIMO

Massive MIMO refers to MIMO systems with a very large number of antennas. The spacing between the antennas may be smaller than the conventional half-wavelength rule. Although massive MIMO is attractive for its potentially very high capacity, unique practical problems such as signal processing complexity, antenna coupling, and channel correlations are being actively researched. Massive MIMO technologies are envisioned to be applicable to commercial wireless networks (e.g., Ref. 3).

Interference Alignment

Interference alignment is a technique with which signals are jointly optimized among a number of interfering links so that all interferences at any particular receiver are aligned within a subspace with a small dimension, leaving the rest of the signal space available for interference-free data transmission. The original concept was proposed in 2008[4] and was soon extended to MIMO cases.[5] Although mathematically elegant, interference alignment still poses many practical problems such as the requirement of central coordination, complexity in computation for optimization, and assessment of benefit in practical system configurations.[6] These are all areas of active research. However, despite being at this early stage of development, interference alignment is already viewed as a potential solution to intercell interferences in a cellular network and is likely to play a key role in future commercial wireless technologies.

APL'S ROLE IN THE COMMERCIAL WIRELESS COMMUNICATIONS DOMAIN

APL has long recognized the tremendous potential benefits of leveraging commercial technologies in the military domain. However, APL has also remained cognizant of the risks associated with improper application of commercial technologies.[1,7] These technologies were developed to solve specific problems in the commercial domain and oftentimes will introduce significant technical or operational limitations when applied to the military domain. The authors believe that responsible application of commercial techniques and technologies has several requirements, primarily significant expertise on commercial technologies and detailed understanding of the intended military concept of operations and operational goals. By bringing to bear both technical expertise and operational insight, APL believes it is uniquely positioned to provide its sponsors tailored, affordable, and effective solutions by leveraging commercial technologies in a responsible manner.

APL's critical contributions are enabled by its profound interorganizational expertise in wireless networking and commercial applications in the military domain. APL staff members teach graduate-level college courses on these subjects. APL staff members write books on these subjects (e.g., Refs. 8–12) as well as magazine and technical journal articles (e.g., Ref. 13). In addition, APL staff members develop and conduct tutorials to educate the community (e.g., Ref. 14).

APL's contributions can take many forms. In some cases, APL staff members leverage their expertise to evaluate existing products and solutions for sponsors.[15] In other cases, APL staff members study how to best apply commercial technology to solve government problems (e.g., Refs. 16–19). Sometimes APL experts research how to modify commercial technologies to better meet the needs of sponsors (e.g., Ref. 20) or how to characterize the limitations of commercial technologies if applied as-is to the government domain (e.g., Ref. 21).

Furthermore, APL experts actively engage in the commercial standards communities on behalf of their sponsors to advocate for their needs and help affect changes to the technologies so they are better suited for as-is use by military and government agencies. APL staff members have long participated in forums (such as the Internet Engineering Task Force) that develop networking standards (e.g., Refs. 22–24) and have contributed in forums such as the Institute of Electrical and Electronics Engineers (IEEE) 802 WLAN (wireless personal area network) standards body and the International Telecommunications Union on behalf of APL's sponsors and their interests.

In many cases, APL experts conduct basic and applied research assisting in the development of new technology concepts and ideas in anticipation of future sponsor needs. This is the case in the area of MIMO communications. APL staff have been actively engaged in research on MIMO technologies. For example, APL researchers have developed delay-tolerant space-time block codes that enable distributed MIMO systems and MIMO relay systems in which precise time synchronization is difficult to provide.[25,26] APL staff also conducted field measurements of MIMO channels in military frequency bands (e.g., Refs. 27–30).

Another focus for APL experts are the security issues in MIMO systems. Because they are sensitive to the spatial signature of the signal, MIMO systems have additional resistance against conventional jammers, which transmit from a single antenna. Therefore, this technology presents unique challenges and opportunities to electronic warfare strategies.[30,31]

SUMMARY

This article briefly discusses the relationship between the commercial and military domains, along with some of the key factors driving commercial development. It also provides a brief overview of some of the key technology trends in the commercial communications landscape and highlights APL's role in this space. It is clear that advances in commercial wireless technologies are increasingly interesting to the militaries of the world. However, there will always be military-specific requirements (e.g., security, the ability to operate in harsh dynamic environments, etc.) that will likely never be fully met by the commercial wireless communications domain. This challenge will require future military network designers to increase their knowledge of commercial solutions but also provide custom modifications to those solutions to meet niche military needs. APL will continue to maintain a unique expertise on commercial wireless technologies and will also bring the discipline and diligence required to apply these technologies in a responsible manner that results in increased capability without unforeseen risk to mission effectiveness. APL remains committed to ensuring that its sponsors have the most effective and affordable solutions possible. It is because of this commitment that APL will strive to maintain the unique combination of technical excellence and knowledge of sponsor needs.

REFERENCES

[1] Burbank, J. L., and Kasch, W. T., "COTS Communications Technologies for DoD Applications: Challenges and Limitations," in *Proc. 2004 IEEE Military Communications (MILCOM) Conf.*, Monterey, CA, pp. 1172–1178 (2004).

[2] Ahmad, M. R., Dutkiewicz, E., Huang, X., and Suaidi, M. K., "Cooperative MIMO Systems in Wireless Sensor Networks," Chap. 7, *Radio Communications*, Alessandro Bazzi (ed.), InTech, Rijeka, Croatia, pp. 123–150 (2010).

[3] Hoydis, J., ten Brink, S., and Debbah, M., "Massive MIMO in the UL/DL of Cellular Networks: How Many Antennas Do We Need?" *IEEE J. Sel. Area. Comm.* **31**(2), 160–171 (2013).

[4] Cadambe, V. R., and Jafar, S. A., "Interference Alignment and Degrees of Freedom of the K-User Interference Channel," *IEEE Trans. Inform. Theory* **54**(8), 3425–3441 (2008).

[5] Yetis, C. M., Tiangao, G., Jafar, S. A., and Kayran, A. H., "On Feasibility of Interference Alignment in MIMO Interference Networks," *IEEE Trans. Signal Proces.* **58**(9), 4771–4782 (2010).

[6] Ayach, O. E., and Heath, R. W., "Interference Alignment—Recent Results and Future Directions," in *Proc. IEEE Radio and Wireless Symp. (RWS)*, Austin, TX, pp. 205–207 (2013).

[7] Burbank, J. L., and Kasch, W. T., "The Application of Commercial WLAN Technologies for Military Operations," in *Proc. 14th Virginia Tech/MPRG Wireless Personal Communications Symp.*, Blacksburg, VA (2004).

[8] Burbank, J. L., Andrusenko, J., Everett, J. S., and Kasch, W. T. M., *Wireless Networking: Understanding Internetworking Challenges*, Wiley-IEEE Press, Hoboken, NJ (2013).

[9] Burbank, J., Kasch, W., and Ward, J., *An Introduction to Network Modeling and Simulation for the Practicing Engineer*, John Wiley & Sons, Hoboken, NJ (2011).

[10] Burbank, J. L., "Security in Cognitive Radio Networks," Chap. 6, *Cognitive Radio Networks: Architectures, Protocols and Standards*, Y. Zhang, J. Zheng, and H.-H. Chen (eds.), CRC Press, Boca Raton, FL, pp. 161–182 (2010).

[11] Burbank, J. L., and Kasch, W. T., "WiMAX Past, Present, and Future: An Evolutionary Look at the History and Future of Standardized Broadband Wireless Access," Chap. 1, *WiMAX Handbook*, S. Ahson and M. Ilyas (eds.), CRC Press, Boca Raton, FL, pp. 1–14 (2007).

[12] Kasch, W. T., and Burbank, J. L., "The Emerging Wireless Internet Architecture: Competing and Complementary Standards to WiMAX Technology," Chap. 1, *WiMAX: Standards and Security*, S. Ahson and M. Ilyas (eds.), CRC Press, Boca Raton, FL, pp. 3–18 (2007).

[13] Burbank, J. L., Haberman, B. K., Chimento, P. F., and Kasch, W. T., "Key Challenges of Military Tactical Networking and the Elusive Promise of MANET Technology," *IEEE Commun. Mag.* **44**(11), 39–45 (2006).

[14] Burbank, J. L., "Commercial Wireless Networking Explained: Building Next Generation Military Networks with Commercial Technology," in *Proc. 2010 IEEE Military Communications (MILCOM) Conf.*, San Jose, CA (2010)

[15] Kasch, W. T., and Burbank, J. L., "The Evaluation of Wireless Networking through ACTION," in *Proc. 2005 IEEE Military Communications (MILCOM) Conf.*, Atlantic City, NJ, pp. 1919–1925 (2005).

[16] Burbank, J. L., and Kasch, W. T., "An IEEE 802.16/802.11 Hybrid TAN Architecture for the Next-Generation National Airspace System," in *Proc. 2005 Integrated Communications, Navigation, and Surveillance (ICNS) Conf.*, Fairfax, VA (2005).

[17] Kasch, W. T., Burbank, J. L., Andrusenko, J., and Lauss, M. H., "Performance of the IEEE 802.11b WLAN Standards for Fast-Moving Platforms," *Proc. 2003 International Telemetry Conf.*, Las Vegas, NV (2003).

[18] Kasch, W. T., Burbank, J. L., and Andrusenko, J., "Physical Layer Performance of the IEEE 802.11b WLAN Standard in Outdoor Applications: A Case Study in Yuma, AZ," in *Proc. 12th Annual Wireless Personal Communications Symp.* (2002).

[19] Burbank, J. L., and Kasch, W. T., "IEEE 802.16 Broadband Wireless Technology and its Application to the Military Problem Space," *Proc. 2005 IEEE Military Communications (MILCOM) Conf.*, Atlantic City, NJ, pp. 1905–1911 (2005).

[20]Burbank, J. L., and Kasch, W. T., "Enhanced Efficiency and Flexibility while Supporting QoS Concepts: An Adaptive MAC Framework for 802.11 WLANs," in *Proc. 2005 IEEE Canadian Conf. on Electrical and Computer Engineering (CCECE)*, Saskatoon, Canada, pp. 37–43 (2005).

[21]Burbank, J. L., Hammons, A. R. Jr., and Jones, S. D., "A Common Lexicon and Design Issues Surrounding Cognitive Radio Networks Operating in the Presence of Jamming," *Proc. 2008 IEEE Military Communications (MILCOM) Conf.*, San Diego, CA, pp. 1–7 (2008).

[22]Mills, D., Martin, J., Burbank, J., and Kasch, W., "Network Time Protocol Version 4: Protocol and Algorithms Specification," Request for Comments 5905, Internet Engineering Task Force (IETF), June 2010.

[23]Cotton, M., Vegoda, L., Bonica, R. (ed.), and Haberman, B., "Special-Purpose IP Address Registries," Request for Comments 6890, Internet Engineering Task Force (IETF), April 2013.

[24]Hinden, R., and Haberman, B., "Unique Local IPv6 Unicast Addresses," Request for Comments 4193, Internet Engineering Task Force (IETF), October 2005.

[25]Hammons, A. R., and Damen, M. O., "Delay-Tolerant STBC for Both Amplify-and-Forward and Decode-and-Forward Cooperative Networks," in *Proc. IEEE International Symp. on Information Theory (ISIT),* Toronto, Canada, pp. 837–841 (2008).

[26]Damen, M.-O., and Hammons, A. R., "A New Class of Asynchronous Distributed Space-Time Codes," *IEEE International Symp. on Information Theory (ISIT)*, Nice, France, pp. 1531–1535 (2007).

[27]Hammons, A. R., Hampton, J. R., Merheb, N. M., and Cruz, M., "Cooperative MIMO Field Measurements for Military UHF Band in Low-Rise Urban Environment," *5th IEEE Sensor Array and Multichannel Signal Processing Workshop*, Darmstadt, Germany, pp. 122–126 (2008).

[28]Hampton, J. R., Cruz, M. A., Merheb, N. M., Hammons, A. R., Paunil, D. E., and Ouyang, F., "MIMO Channel Measurements for Urban Military Applications," in *Proc. 2008 IEEE Military Communications (MILCOM) Conf.,* San Diego, CA, pp. 1–7 (2008).

[29]Hampton, J. R., Hammons, R. A. Jr., Cruz, M. A., Merheb, N. M., Paunil, D. E., and Ouyang, F., "Multiple-Input Multiple-Output (MIMO) Channel Measurements for Urban Military Applications," *Johns Hopkins APL Tech. Dig.* **30**(2), 135–143 (2011).

[30]Ouyang, F., "Electronic Warfare Design Options Against Commercial Grade MIMO Systems," in *Proc. 2012 IEEE Military Communications (MILCOM) Conf.*, Orlando, FL, Classified Sessions (2012).

[31]Ouyang, F., "Jamming Effectiveness against Spatial Multiplexing Multiple Input Multiple Output (MIMO) Communications Systems," in *Proc. 2010 IEEE Military Communications (MILCOM) Conf.*, San Jose, CA, Classified Sessions (2010).

THE AUTHORS

Julia Andrusenko is a member of APL's Senior Professional Staff and the Chief Engineer of the Tactical Wireless Systems Group. She is a lead communications engineer supporting a large electronic warfare program. Her expertise is in the realm of RF propagation prediction, communications vulnerability, and MIMO technologies. In 2013, she coauthored a book titled *Wireless Networking: Understanding Internetworking Challenges*, which won the APL Hart Prize and served as a basis for this article. **Jack L. Burbank** is the Assistant Group Supervisor of the Tactical Wireless Systems Group and a member of the Principal Professional Staff at APL. His recent work is in the areas of wireless network security, cellular communications, and cognitive networking. **Feng Ouyang** has nearly 20 years of experience in digital communications. He is a section supervisor in APL's Tactical Wireless Systems Group and a Senior Professional Staff member. His current research interests include wireless communications systems, multi-user MIMO technologies, electronic warfare, and cyber operations technologies. For further information on the work reported here, contact Julia Andrusenko. Her e-mail address is julia.andrusenko@jhuapl.edu.