NSF/ONR/ARL Workshop on

Future Challenges of Signal Processing and Communications in Wireless Networks

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Contents

1 Introduction

Under the sponsorship of the National Science Foundation, the Office of Naval Research, and the Army Research Laboratory-CTA, a workshop entitled "Future Challenges in Signal Processing and Communications in Wireless Networks" was held on Sept 5-6, 2002 at Cornell University. The objective of the workshop was to identify pressing research issues and research directions in communications, signal processing, and wireless networks. During the two day workshop, participants examined an array of current and emerging research trends relating to three major themes: fundamental limitations in wireless networks; emerging techniques and applications of signal processing and wireless communications; and industrial and DoD perspectives. For each theme, the workshop featured keynote speakers followed by panel discussions and question-answer sessions.

Plenary presentations were given by

- David Tse, Professor, University of California at Berkeley
  Information Theory at the Extremes
- John Treichler, Chief Technical Officer, Applied Signal Technology, Inc.
  The Impact of Economics and Technological Trends on New Wireless Services
- Dipankar Raychaudhuri, Professor, Rutgers University
  Research Challenges in Wireless Communication and Networking
- Rajiv Laroia, CTO, Flarion Technologies.
  OFDM for Mobile Wireless Internet?
- John W. Gowens, Division Chief, Army Research Laboratory
  C^4I for the Objective Force
- Ken Young, Executive Director, Applied Research, Telcordia Technologies
  Research Challenges for Military Networking
- Dennis McGregor, Program Manager, Office of Naval Research
  Navy Perspectives on Wireless Communications and Networking

Plenary presentations can be found at `http://acsp.ece.cornell.edu/NSF`

Three panels were formed:

- Panel on Fundamental Limits and Future Challenges
  Panel Lead Anthony Ephremides, University of Maryland, College Park.
  Panelists Toby Berger, Cornell University
  John Proakis, Northeastern University
  Ramesh Rao, University of California, San Deigo
  David Tse, University of California, Berkeley

- Panel on Emerging Theory and Applications
  Panel Lead Lang Tong, Cornell University
  Panelists Georgios Giannakis, University of Minnesota
  Dennis Goeckel, University of Massachusettts
  Dipankar Raychaudhuri, Rutgers University
  John Treichler, Applied Signal Technology, Inc.

- Panel on DoD and Industry Perspectives
  Panel Lead Ananthram Swami, Army Research Laboratory
  Panelists John W. Gowens, Army Research Laboratory
  Rajiv Laroia, Flarion Technologies
  Dennis McGregor, Office of Naval Research
  Jason Redi, BBN Technologies
  Ken Young, Telcordia Technologies

The authors of this report met after the workshop and summarized the main findings.

2 Fundamental Limits in Wireless Communications and Networking

There is an important role for information theory in the development of new wireless networked systems. Wireless networking is a very different and significantly more complex field compared to point-to-point wireless systems that have been addressed so successfully by information theorists. Whereas obtaining performance characterizations that are as simple and as compact as, e.g., channel capacity in point-to-point problems may be unrealistic, information theoretic approaches might help identify tradeoffs and relationships among key variables. That is, the ideas that inspired Shannon to develop the foundation of information theory have a very relevant role to play in the context of wireless networks, at least in meaningful asymptotic regimes in signal to noise ratio (SNR) and in the size of the network. Indeed, researchers with an information-theoretic background have made headway in establishing some fundamental perimeters of this field that is experiencing a continuing growth with new applications.

Fundamental roles of diversity need to be understood in the information theoretic context. In wireless communications, fading was long thought of as a channel impairment that had to be mitigated. But more recent work has established the possibility of taking advantage of multipath propagation to achieve higher degrees of diversity, thus increasing the effective data rates that can be delivered over wireless channels. Similar observations have been made about mobility, and also about interference. In these examples, a conventional shortcoming is, in fact, a source of diversity in disguise. Furthermore, the recent realization that the use of multiple antennas leads to the potential creation of independent parallel paths, and hence to an increase in point-to-point capacity, has fueled significant interest in Multiple-Input Multiple-Output (MIMO) systems. The use of such systems in multiuser environments opens new possibilities for introducing and exploiting additional diversity. An important area of research in wireless networks is therefore the characterization of different forms of diversity, together with constructive methods that can exploit them to achieve higher communication performance.

Issues of stability, source burstiness, delay constraints, multi-hop communications, and scaling behavior in large networks are fundamental aspects of network communications (and not limited to wireless networks). Although this has been known for some time, the promise of applying control and optimization theories to problems in communication networks is still to be fulfilled. Specifically, in the context of wireless networks, the coupling of layers and the important role of the wireless link in determining network connectivity provide new means for exploring network control issues. For example, issues such as radio frequency transmission power and transmission rates directly affect the graph topology of a wireless network.

There appears to be a point of departure from classical networking wisdom in the design of emerging wireless networks. One could argue that the success of the Internet is, to a large extent, due to a strict separation of layers that was adhered to in its design: the network infrastructure was designed primarily with a flexibility goal in mind, independent of the applications. The result is, indeed, an extremely flexible network, although the price to pay for this is gross inefficiencies in the operation of the network. Wireless networks are inherently more resource constrained than high-speed wired IP networks, and therefore it is unclear whether such a one-size-fits-all approach will be feasible in this case. It appears to be the case in emerging wireless networks (such as sensor networks) that application-specific considerations might have a strong influence on the network design/provisioning tasks.

The provision of Quality of Service (QoS) guarantees is a problem far from solved in most networks, and wireless networks bring extra complexities to this important problem. To start with, there are new QoS parameters that make sense only in the context of a wireless network, such as throughput measures that incorporate a "geographical" element (such as bits/sec/Hz/meter). Further, in a network environment, more classical QoS parameters (such as BER, SNR, and energy consumption) have an impact that extends well beyond the individual link level (e.g., on network connectivity, interference levels, etc.). The strong coupling and interdependence among the traditional layers of networking are strengthened in the wireless case because of the crucial role played by the wireless link and the effects of Medium Access Control. Joint optimization across layers is certainly desirable, but oftentimes difficult to implement in practical systems. At a minimum, however, capturing these dependencies through programming or control interfaces among the layers will permit design choices that will improve communication performance.

The design of large scale sensor networks poses a set of new challenges to information theory, communication theory, and network theory. Such networks are characterized by the large size of the network both in term of the number of nodes and in term of the geographic area the network covers. Furthermore, each node is severely constrained by its computation and transmission/receiving power. Such extreme constraints (very large network size and low node power) require an understanding of the performance limit of such networks. Important aspects of sensor networks such as duty cycling, data burstiness, finite battery life, and lack of global probabilistic description create additional challenges to developing an information theoretic approach.

While the importance of information theory for wireless networks is recognized, we are still in the early stages of developing a coherent set of theories that can be applied to emerging applications in large scale sensor and mobile ad hoc networks. Critical in this approach is the incorporation of unique characteristics of wireless networks such as energy constraint, information transport, and traffic burstiness.

3 Emerging Theory and Applications

3.1 Novel Diversity Techniques and Signal Processing

The critical role of diversity techniques in wireless has been recognized since the 1960s. In recent years, however, advances in digital signal processing and device technology provide options beyond the classical temporal and frequency diversity techniques, especially when diversity is considered in a multiuser environment and in the context of wireless networking.

Theoretical analyses and experiments predict substantial diversity gains from the use of multiple antennas although many issues remain open at both the theoretical and implementation levels. Fundamental design tradeoffs require further study. This includes coherent vs. non-coherent techniques, complex field vs. finite field coding, pilot aided vs. (semi)blind algorithms, and diversity vs. achievable rate.

There is a potential to improve network performance if multiuser diversity can be exploited. Multiuser communications over fading channels are asymmetrical; at any time, some users may have more favorable channel conditions than others, and the set of users with good channels varies with time. Performance can be improved by scheduling appropriate subsets of users for transmissions and allocating network resources accordingly. Depending on the nature and the availability of the channel state information (CSI), such scheduling can be made either by a central controller or at each node in a decentralized fashion. Adaptive scheduling and resource allocation schemes need to be developed. Practical constraints such as delay requirements, fairness, and protocol overheads must be taken into consideration.

There is a wide range of algorithmic issues that need to be tackled at both the transmitting and receiving ends. The acquisition of channel state presents difficult challenges: new techniques that exploit packet structures such as headers, cyclic prefix and sync/address bits should be considered; efficient pilot assisted training schemes are needed; channel estimation error and its impact on performance need to be quantified. The development of tractable statistical (propagation) channel models, particularly in the wideband context, is critical, as this will lead to a proper characterization of estimation techniques and uncertainties in CSI. Alternative noncoherent techniques that are insensitive to channel uncertainties are valuable, and tradeoffs should be examined. Processing complexity is a limiting factor for high data rate reliable communications, particularly in applications where the 'mobile' node may be power and energy constrained. High performance iterative techniques may be complemented by a batch pre-processing step that provides effective initialization strategies. Adaptive algorithms are crucial not only for fast fading channels but also for channels with bursty traffic where packets are transmitted at random times over different fading channels.

3.2 Cross-Layer Design in Wireless

Cross-layer design emerges as a promising methodology for wireless networks. Examples of cross-layer design include the integration of antenna techniques, MIMO physical layers, and medium access control. The bursty nature of wireless data and the presence of interference from other services should be taken into account in source/channel coding, in multiple access schemes, and in the design of signal processing algorithms. Cross layer design may be crucial in supporting multimedia applications where Quality-of-Service (QoS) requirements can be accommodated with a cross layer design that is adaptive to variations of the underlying physical channels. For example, source coding may be jointly designed with channel coding and routing. Packet structures may be designed to reflect QoS prioritization and the need for reducing protocol overhead.

With the proliferation of wireless LAN, bluetooth and the potential use of ultra wideband radio, the need arises to investigate the coexistence among multiple networks, some operating in the infrastructure mode and others in an ad hoc fashion. The design of large scale sensor networks must deal with a set of new challenges not present in cellular networks: the available power at each sensor node is severely constrained, and vertical coupling among layers with judiciously chosen parameters may prove to be necessary. Furthermore, traffic in sensor networks is highly correlated, which calls for distributed coding techniques coupled with energy aware and power efficient medium access control and routing. The design methodologies must scale with the number of nodes in the sensor network as well as its coverage area.

As a new design paradigm, the cross-layer approach raises many open issues: How many layers should be integrated? Which ones? How can stability be maintained while protocols at different layers adjust their parameters? How does one take into account the overhead required in cross-layer design, and the delays incurred in the exchange of parameters? What are useful metrics that capture this overhead in terms of bandwidth, energy, complexity, delay, and other relevant parameters? What is the expected gain from the joint optimization of cross-layer protocols?

3.3 New Challenges in Ultra Wideband Radio

Communications under the ultra wideband (UWB) regime is of emerging interest at both the theoretical as well as the practical implementation levels. Given the long history of UWB in radar systems, its potential applications in geolocation, tagging ("RF IDs"), inventory control, and as a supplement to GPS, are obvious. But in establishing the realistic potential of UWB communications (short range, indoor LANS, sensor nets, LPI modes, etc.), there is a need to develop realistic and tractable models that capture not only the spectral characteristics of the wideband propagation channel, but also the antenna response, the impact of unstructured interference, and the potential ability to resolve closely spaced multipaths, particularly with pulsed signaling. Receiver implementations for UWB systems are particularly challenging due to interference, synchronization, and channel estimation issues. Recent information theory analyses indicate that the requirement of high quality channel estimates greatly inhibits system operation over large bandwidths.

Fundamental issues relating to multiaccess protocols, modulation schemes, and signal processing algorithms need to be addressed while taking into account the characteristics of the wideband channel, the presence of very large number of multipaths, the difficulty in timing and channel acquisition (particularly in the episodic or duty-cycled mode), the existence of interference from narrowband and other UWB devices, the apparent necessity of sub-Nyquist sampling, and the limitation of DSP (such as ADC). Innovative approaches to UWB networking that combine physical and higher layers will be required. These issues will impact the prototype single user UWB radio in terms of complexity, size, weight and power.

The co-existence issue: i.e., the impact on (and of) conventional narrow-band radio systems, and wideband radars must be quantified. There is an apparent need to revisit robust signal processing techniques in order to mitigate the UWB transients or impulses that may be seen by a narrowband receiver. Innovative all-digital radio receiver design can be facilitated only by the development of low-power small footprint high precision high rate analog-to-digital converters (ADC) that can be embedded in a mobile device. Tradeoffs with alternative higher rate but lower precision sampling schemes must be studied. The UWB signal design problem cannot be decoupled from antenna design, i.e., the design of miniaturized, perhaps directional, wideband antennas that ideally do not distort the signal.

Thus, there are opportunities for multidisciplinary approaches involving modulation, coding, signal processing algorithm development, protocol design, VLSI and RF front-end (antenna, ADC, variable delay correlator) design.

3.4 3G Wireless and Beyond

Over 56% of the nation's households now subscribe to cellular services. The phenomenal increase in the number of cellphone users in recent years has started to strain existing wireless networks and overcrowded local airwaves. While the need to go beyond the second generation digital cellular is undisputed, the path to the third generation (3G) and beyond is nebulous, with both economic and technical factors affecting future directions. Among future trends are broadband wireless access in an integrated cellular network, high speed wireless LAN/PAN for hot-spot applications, home network, and sensor networks.

There are two architectures being considered for these future commercial systems, both rely on the widely held belief that commercial networks will only require a single wireless link—the last one to the user. The first architecture is a traditional cellular paradigm that will be more properly matched to the concept of the "wireless Internet" than are current 2G and 3G systems, and supports the notion of "anytime, anywhere" communication. However, there also is significant potential in a second approach, which adopts a "many-where, many-time" philosophy that exploits the overall efficiency of only short-range transmission. This latter technology, often referred to as "Info-station", transmits data to a user only when that user is within a short distance of an access point. Thus, although the user does not have ubiquitous access, a number of well-located access points will allow efficient data transmission to users for much of their needs. While both technologies focus primarily on data distribution, there is also the problem of data updating of a (possibly) distributed database by multiple users, with possibly conflicting data, with application, for example, in disaster recovery, where emergency personnel may want to update a common view of the disaster area.

As wireless modems become faster and ubiquitous, there is a cogent need for key innovations at both the algorithmic and hardware levels. Specifically, signal processing techniques in MIMO systems and adaptive antennas are crucial to future wideband wireless. Key technological components include compact RF design, MEMs, low-power and ultra wideband sensors, mixed signal design, and software defined radio operating at 10-100 Mbps, and beyond.

There are a number of higher layer issues that arise in connection with information delivery: providing QoS with heterogeneous and time-varying radios, delivering the "right information" at the "right time and to the right locations"; utilizing caching and content-based location aware multicasting, and media scaling to match PHY capabilities.

At the system level, fundamental research must address the scalability of wireless networks, radio resource management, spectrum sharing and interference avoidance. The proliferation of wireless devices and non-cellular networks calls for novel protocols. Examples include new MAC protocols that integrate physical layer innovations, new routing protocols for self-organizing wireless networks, and security protocols for wireless.

A driving goal for future commercial systems is the "wireless internet". The implementation of such a vision must not be forced onto networks originally designed for voice traffic. The design of wireless data network must allow the network to handle applications not yet conceived at this time, in much the same way that the current internet has been very flexible in its support of new applications.

4 DoD and Industry Perspectives

4.1 Mobile Ad Hoc Networks

Research required to support future commercial networks is vastly different from that required to support military networks. In any of the currently-envisioned architectures for future commercial systems, a fixed infrastructure comprises a large part of the network and only the first and last links in a transmission are possibly wireless. In contrast, military communication networks have to be rapidly deployable in new environments; since this often implies a mobile infrastructure, military networks will rely very heavily on large portions of the network that are wireless, self-configuring, multi-hop, etc. Military radios are also subject to constraints on size, weight and power, much more so than commercial radios. Additional significant concerns are anti-jam, low-probability of detection, and low-probability of intercept of the waveforms. The network topology may be dynamic due to mobility or loss of the nodes, and the RF environment may be harsh. Node authentication and verification are other challenges. Thus, the notion of dual-use networking technology is tenuous, and it is not anticipated that commercial radio companies will fund research that overlaps with the interests of the military.

As commercial companies reduce their support of basic research in the key technologies required for robust rapidly-deployable military networks, the investment by the military in basic research will need to be increased if the crucial goal of information superiority is to be achieved. The vision for these future military networks is that they will be "network-centric" as opposed to the traditional "platform-centric." This reflects a shift away from optimized local communications among troops and vehicles to seamless communication across the battlefield between platforms, which makes security and interoperability important. For example, in any theater, the military might be employing a number of different radio technologies amongst a number of different services, and the ability of these disparate radio technologies to communicate securely will be paramount.

An ad-hoc (peer-to-peer) communications network is critical in rapid-deployment situations. In such situations, everything is in motion, including the infrastructure, which clearly differentiates the military (or emergency) network research problems from those of commercial systems. Because the elements of the network will move in an unforeseen manner which depends on the specific battlefield situation, it is imperative that the network be self-organizing and rapidly reconfigurable. In addition, there may be no central authority to configure and optimize the network; thus, a set of units must be able to configure regardless of their heterogeneity in an environment where there may very well be information countermeasures (jamming, spoofing, etc.) deployed by the enemy. The problems of node authentication and verification are challenging here.

In addition, vulnerability assessment and fault detection will need to be considered. These issues have often been considered for various commercial networks, but this is in a static network configuration. In the mobile battlefield, the network architecture will constantly be changing, and it is imperative that the network recognize its current vulnerabilities and the ability to detect faulty and/or malicious nodes. The network will also suffer from intermittent connectivity, because, unlike most commercial networks, which can be designed with a reasonable link margin to guarantee network connectivity, military networks can become disconnected on the mobile battlefield due to geographical disparity, node loss, the need to go off-the-air, jamming, etc. Various families of algorithm (such as routing) will need to be reconsidered for such a network.

Clearly, the challenging problems in military networks can benefit from a cross-layer design philosophy. This does not necessarily imply joint optimization of multiple layers, which often suffers from complexity problems, but implies at least an understanding of how the layers interact, and designs so that the layers are matched. For example, as with single military communication links, it will be imperative that the network be robust to the information countermeasures of the adversary, and it is likely that interlayer optimization can aid in this traditionally physical-layer area. For example, the network may want to rapidly reconfigure to avoid a badly jammed link, thus releasing the physical layer from the costly proposition of making every link robust.

At the physical layer, continued research in LPI/LPD/AJ operation is critical, since it is imperative that the adversary not only be unable to intercept messages but also unable to detect the location and movements of assets. All of this must be achieved under the constraint that the radios in the network be small and lightweight, as they must often be carried by soldiers who are already loaded down with gear. This makes low-power operation imperative to extend the life of lightweight batteries.

4.2 Sensor Networks for Military Applications

Sensor networks in conjunction with other data-gathering units (such as UAVs) will continue to be an area of research interest. Geographically dispersed large arrays of, perhaps disparate, sensors, with some self-organizing capability, will enhance the capability of distributed sensing. Such networks will be used for battlefield surveillance, and may provide replacement for landmine fields.

Sensor networks may be considered to be large collections of dumb sensors, in contrast with networked radar systems which are well described as small networks of very smart sensors. Sensor nets provide a new way for target detection, localization, and tracking; such 'targets' need not be RF or acoustic emitters, but could include bio-chemical agents. The sensors may have different modalities leading to issues in information fusion.

Issues related to network organization, topology, and information processing associated with such low-energy large scale networks are challenging. The topology of the network may be dynamic, both due to mobility (such as in robotic networks) or due to node loss or duty-cycling.

The sensors are expected to be cheap, with severe energy constraints, so that local processing may be limited. On the other hand, the sensor deployment may be dense, which raises interesting issues regarding the tradeoffs between processing at the local vs. network levels. Issues related to interrogating the sensors, downloading data to the sensors, and control of sensors, pose challenges to traditional notions of medium access control, particularly for applications where the sensor nets may be deployed in in difficult urban terrain, or in tunnels, or under dense foliage.

Sensor networks can be active where sensors collectively perform certain tasks. For example, while each sensor may have limited transmission power, collectively, a large number of sensors can perform the task of a powerful jammer. Similarly, a widely distributed field of sensors can jointly determine the location and trajectory of multiple targets. All these applications require a fundamental understanding of the communication and networking aspects of large scale sensor networks as well as tradeoffs in sensing, signal processing and communications. Low-energy scalable protocols are critical, and mathematical tools for the analysis of large scale networks must be developed.

4.3 Ultra Wide Band Radio for Military Applications

Ultra-wideband (UWB) radio has been promoted for a number of different applications, ranging from high-bandwidth commercial communication applications (e.g. connecting a computer to a printer in an office) to extremely robust low-rate military communication applications such as the identification of friend-or-foe (IFF) in an urban environment. Low-complexity UWB radios might find applications in sensor networks. In addition to issues discussed in Section 3.3, military specific challenges must be studied. For military networks, the wide bandwidth allows excellent material penetration and robustness to fading, which would make it ideal for positioning and IFF, stealthy low rate or burst mode high rate communications, as a supplement to GPS, and as a potential technique to acquire precise network timing. Co-existence with other radios will remain an important area of research—both for commercial and military applications. Single and aggregate interference models must be developed, so as to quantify the impact of the potential mass proliferation of low power UWB radios on existing narrowband radios (measured, for example, by the BER degradation of the victim receiver, or impact on channel capacity), and on wideband systems such as airborne radar. Conversely, the impact of the growing number of narrowband systems on UWB radio must also be studied.

The answers to some of the above questions on the applicability of UWB radios will depend largely on progress in UWB transmitter/receiver design. Ultra-wideband radio does not fit the narrowband models on which much of modern communication and signal processing theory is built. In particular, the large bandwidth causes interactions between the signal waveforms and system antenna in ways that right now largely have to be investigated separately for each pulse shape, propagation environment, and antenna pair. Thus, research is needed to understand the ultra-wideband system model and develop communications and signal processing algorithms.

The ultra wideband radio channel model is poorly understood, and models are lacking. Parsimonious statistical channel models, based on EM propagation modeling and substantial channel measurements, could be the key to efficient exploitation of multipath diversity. Scaling laws associated with large bandwidths could provide useful insights.

Key hardware challenges include high rate, high precision sampling devices (ADC). Indeed, analog vs. digital implementations defines a technology breakpoint, since potential applications are limited by the power consumption and footprint of the ADC. Multi-carrier approaches, channelized receivers, and tradeoffs in rate vs. precision of the ADC merit careful study.

The UWB signal brings it with challenges such as wideband DOA estimation and interference / transient rejection, rapid acquisition and synchronization issues, which are made more difficult by the episodic nature of the UWB signal, and the potentially many narrowband and UWB interferers in the RF environment. Optimal training and signal design for such interference-limited episodic systems need investigation. The potential of UWB to yield precise location or equivalently good intra-network timing provides an opportunity to be exploited in innovative cross-layer protocol design.

5 Recommendations

One of the key lessons that has been learned from the recent economic downturn in the telecommunications industry is that commercial industry by nature constantly focuses on cost-effective solutions. Specifically, technology is business-driven and more focused on short-term interests, which is projected to provide less support for basic research. In the interest of long term economic growth of this country, NSF and DoD agencies must continue their commitment to supporting long term and fundamental research. While medium and large collaborative projects allow focus research in key areas, funding for individual PI projects should not be sacrificed.

Workshop participants identified the following promising research directions.

Fundamental Limits NSF and DoD should support research on information and network theoretical approach to wireless communications and networking. Specific areas include

- scaling laws for large scale low power networks;
- information theoretical understanding of diversity;
- network coding theory and cross layer designs;
- information theory with nonclassical constraints such as finite battery life, the lack of global descriptors, and traffic burstiness.

Diversity Techniques and Signal Processing Fundamental research is needed in exploiting diversities in the network context. Specific research areas include

- the use of antenna in wireless networks for MAC and higher layer functions
- the exploitation of diversity among spatially distributed nodes;
- collaborative relaying and transmissions;
- multiuser coding and signal processing techniques for MIMO channels;
- the acquisition of channel state information the exploitation of channel state information in diversity techniques;

- new algorithms to deal with asynchronous bursty interferers.
- signal processing techniques that exploit packet structure.

Cross-layer Designs of Wireless Networks Cross-layer design is a promising but not well established methodology. Research at both theoretical and implementation levels should be supported. Examples of such efforts include

- novel coding and signal processing techniques that incorporate higher layer protocol information;
- new MAC and routing protocols that take into account physical layer capabilities such as space-time coding, interference cancellation, and spatial diversity techniques.
- interference avoidance and management techniques jointly developed with MAC and routing protocols.
- source and channel coding techniques that take into account properties of fading links and physical layer signal processing.
- novel signal processing techniques applicable in large scale sensor networks.
- PHY and MAC layer techniques that take into account correlated traffic in sensor networks.
- Novel coding and network protocols for delay sensitive applications.

Ultra Wideband Communications Substantial research effort is needed in the area of communications using ultra wideband radios. Fundamental issues and research topics include

- channel modeling, estimation and its impact on performance;
- timing and channel acquisition techniques for episodic systems;
- analog-digital hybrid signal processing techniques;
- compact, efficient, wide band antenna design;
- co-existence issues and interference management;
- VLSI circuit design for UWB such as high rate low-power ADC.

Systems Issues The evolution beyond the current generation's digital cellular systems requires significant support of research activities in a number of new areas.

- Scalability issues must be addressed for signal processing and protocol designs. Of particular importance are the scalability of capacity in sensor and ad hoc networks, the efficiency of spectral utilization in large scale networks, and the coexistence of various wireless networks and services.

- Novel protocols and architectures for wireless LAN and hot-spot applications are needed. Specific areas include MAC protocols for 802.11x, 803.15x, and sensor networks, mobility protocols beyond mobile IP, routing protocols for ad hoc networking, and protocols for network security.