Future Challenges of Signal Processing and Communications in Wireless Networks

Mr. Faisal Khan

M.E. in Electronics and Tele communication (Microwave engineering)

I. INTRODUCTION:

Fundamental Limits in Wireless Communication 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.

II. EMERGING THEORY AND APPLICATIONS

2.1 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 ploited. 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 busty traffic where packets are transmitted at random times over different fading channels.

2.2 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 busty 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 (Quos) 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 Quos 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?

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