Wireless Networks

Communication and Control

by Babak Hassibi

Due to recent advances in wireless technology and RF circuitry, wireless devices (and other devices enhanced with wireless capabilities) have become more and more ubiquitous. By all appearances, this trend will continue. Furthermore, with advances in sensor technology, it is now possible to deploy a multitude of small sensors capable of exchanging information in a wireless fashion. With minimal infrastructure, bandwidth and power, such devices can provide mobile ad-hoc networks (MANETs) and sensor networks that deliver nearly arbitrary amounts of relevant information to any location at any time. The realization of such powerful sensor networks presents many research challenges since the networks need to self-organize, operate in a distributed fashion, and be robust with respect to changes in the network topology, time-varying traffic types, etc. The work supported by the Lee Center in the Hassibi group, as further explained below, has attempted to address some of these research challenges.

One normally thinks of a network as a collection of nodes with edges connecting them. However, in a wireless network, things are more complicated and we need to dispense with this picture. In particular, wireless networks have the following distinguishing features: shared communication medium; interference, i.e., the received signal on each node is the sum of all incoming signals; broadcast, i.e., the transmit signals on all outgoing edges are identical; path-loss, i.e., the signal strength depends on the distance between nodes so that both geometry and topology are important; and fading, i.e., the signal strength undergoes random fluctuations due to changes in the environment, such as might be caused by the mobility of sensors. Traditional methods have viewed these as "deficiencies." However, new approaches might be able to exploit them for improved performance.

The first wireless networks (deployed in the 1950's) consisted of a single base station with large coverage area in an urban center, along with mobiles. However, in these early systems only a few users could be accommodated due to interference. The theory of cellular networks was developed at Bell Labs in the 60's and 70's. This theory used path-loss to allow for frequency re-use, and thereby could accommodate many, many more users. However, it was not until the 1980's that the first such system was deployed by Motorola in Chicago (called AMPS—American Mobile Phone System). An interesting anecdote is that in the 1970's AT&T hired McKinsey & Company to study the feasibility of deploying a cellular system, but they were discouraged from doing so because McKinsey believed there was not a large enough market! Since the first commercial systems, cellular networks have rapidly evolved in terms of capacity, cell size, and access schemes. We now also have next generation wireless networks such as WLAN's (802.11's), blue tooth, Wi-Fi, Wi-Max, etc., along with the emerging sensor and ad hoc networks mentioned earlier.

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Some Research Highlights

In what follows, we will briefly describe some of the research activities performed under the support of the Lee Center.

(1) Multiple antennas in cellular networks: To increase the capacity of cellular systems, it has been proposed to use multiple transmit antennas at the base station and (possibly) multiple receive antennas at the mobile users. We have studied the capacity of such a network and have shown that if each cell has a base station with M transmit antennas and there are n mobile users, each with N receive antennas, then the information-theoretic capacity scales as $C = M \log\log nN$. This shows that additional hardware investment at the base station is worthwhile, since the capacity increases linearly with the number of transmit antennas M, however, additional hardware expenditure at the mobiles is not, since the capacity increases only double-logarithmically in the number of receive antennas N.

A major challenge in delivering this capacity is that the transmitter needs to know the channel state information to all the n mobile users. This requires an unreasonable communication overhead and is not feasible in situations where due, for example, to mobility, the channels change rapidly. We have proposed a scheme (referred to as random beam-forming) which comes very close to achieving the information-theoretic capacity, yet requires minimal communication overhead. Random beam-forming, and its variants, are currently used in the Wi-Max standard. We have also studied scheduling problems in such systems (these become especially challenging, since there are not only variations in the users' demands, but also in the users' channel conditions which determine the rates to which they can be transmitted). In particular, we have studied the trade-off between the capacity of the system and the fairness in serving the different users and show that if the number of transmit antennas at the base station is on the order of the logarithm of the number of users, formally $M = O(\log n)$, then one can simultaneously both maximize the capacity and achieve fairness.

(2) Privacy in wireless networks: Since wireless is a shared medium, it is particularly susceptible to eavesdropping and therefore security is a major concern. An information-theoretic approach to guaranteeing security is through the notion of secrecy capacity, defined as the maximum rate at which two users can reliably communicate so that an eavesdropper can infer zero information from the communication of the two users. We have computed the secrecy capacity of a system in which the users, as well as the eavesdropper, have multiple antenna transmitters and receivers (as is the case in a cellular network). The solution of this long-standing, open problem has generated a great deal of follow-up research, and a large effort is underway to construct practical schemes that achieve this information-theoretic secrecy capacity.

(3) Capacity of wireless erasure networks: Unlike point-to-point information theory with a single transmitter and single receiver, where the information-theoretic capacity is well known and completely characterized, the information-theoretic capacity of almost all multi-user systems (with multiple transmitters, receivers and relays) is unknown. By fiat, the capacity of wireless networks in the general case is not known. We have recently proposed a simplified model of wireless networks, which we refer to as wireless erasure networks, where the transmitted packets are either perfectly received across links or dropped altogether with some probability. This applies in packet-based communication schemes (such as Internet protocols with in-packet error detection). With the model we have been able to compute the multi-cast capacity for transmission of the same information to multiple destinations in the network. The ideas used are similar to those used in network coding and the capacity is essentially determined by a certain "min-cut". This was arguably the first non-trivial class of wireless networks for which a capacity result could be obtained and it has generated significant further work in the research community.

(4) Estimation and control over lossy networks: Many complex systems (such as the power grid and many chemical plants) are controlled remotely with measurement and control signals being sent across a possibly lossy network. The random losses that occur in the network (both in terms of the measurements being dropped before being received by the estimator, or the control signals being dropped before reaching the actuators) have an obviously adverse effect on the system performance (and perhaps its stability). We have studied the design of optimal estimators and controllers in the face of such a lossy network. We have also determined universal laws (akin to the central limit theorem) that occur in such complex lossy control systems.

Future Work

The convergence of communications and signal processing, or rather communications and computation, has long been recognized. At an abstract level this is evident through the use of personal computers as communications devices (e.g., email and internet). Likewise, the relationship between signal processing and control has long been recognized. With recent technological advances, a complete convergence of communications, computation and control has begun.

Nowhere is this convergence more evident than in the mobile wireless networks that will emerge in the coming decades. As mentioned earlier, due to advances in sensor technology and radio-frequency circuitry, wireless devices will have the capabilities of sensing and exchanging information in a centralized and also distributed and ad-hoc way. Moreover, as these devices couple with more complex systems, they will be able to function as actuators and thereby influence the environment in which they operate. This opens up a host of exciting possibilities in environmental monitoring and control, surveillance, flight formation, as well as decentralized sensing and control of industrial plants, the power grid, and traffic. It also presents many research challenges that we will continue to pursue. Two major ones are now described.

“With recent technological advances, a complete convergence of communications, computation and control has begun. ”

Network information theory: A stumbling block in the design of wired and, especially, wireless networks is the paucity of results in network information theory. In fact, the information-theoretic capacity of even the simplest networks remains open. Therefore much of the research in the community has focused on very specific models that are amenable to analysis (such as the wireless erasure networks mentioned above), or on asymptotic results that study various scaling laws for very large networks.

We have developed a new formulation of network information theory problems that reduces them to solving a linear optimization problem over the convex space of entropy vectors. The space of entropic vectors is a convex cone of 2^n-1 dimensions (where n is the number of random variables) and, if known, reduces network information theory problems to simple convex optimization. The challenge is that a characterization of this space is not known for n>3 and so our observation does not immediately solve network information theory problems; it rather reveals its core. Among others, this problem has connections with group theory, matroids, lattice theory, and determinantal inequalities. We have been actively studying this space and to date have constructed various inner and outer bounds.

Real-time information theory: Information theory, as developed by Shannon in the 40’s and 50’s and which serves as the theoretical core of today’s telecommunications industry, ignores real-time constraints and allows for arbitrarily long delays in decoding the transmitted information. Control theory, on the other hand, ignores information-theoretic considerations and yet deals with real-time constraints upfront. We are therefore studying ways to combine communications and control theory in the context of a wireless network where the devices need to make real-time decisions but communications takes place over unreliable, time-varying channels. LEE

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