Wireless Networks : Analysis, Protocols, Architecture and Towards Convergence

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Abstract

We present a brief account of some recent work of our group in four areas:

(i) Information theoretic limits on how much traffic wireless networks can carry.

(ii) Information theoretically optimal strategies for operating wireless networks.

(iii) Protocols for media access control, power control, clustering, and routing.

(iv) The importance of architecture in the oncoming convergence of control with communication and computing.

1 Information Theory and Optimal Operation

Wireless networks do not come with links. Nodes simply radiate energy. Hence, they can cooperate in all manner of ways to facilitate information flow in networks.

One mode of cooperation is the following:

(i) Relay packets from node to node until they reach their destination.

(ii) Fully decode a packet at each hop.

(iii) While decoding a packet at each hop, simply treat all interfering transmissions as noise.

Currently, intensive protocol efforts are focused on realizing this mode of operation, which we will call the *multihop mode*.

This mode of operation gives rise to several protocol needs. Due to the multihop strategy, one needs a routing protocol to find paths from sources to destinations [1]. Since all interference is treated as noise, one would like to regulate the number of interferers; this gives rise to the need for a medium access protocol. Further, since transmissions interfere with each other, one needs a power control protocol to regulate the powers of transmissions.

However, one can envisage other modes of cooperation. To stretch the imagination and illustrate the possibilities that arise in the wireless radio world, consider the following mode of cooperation.

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Node A transmits a signal which is designed to cancel the interference created by node B's transmission at node C. (This is a mode of cooperation which attempts to mitigate the negative interference rather than enhance the positive signal.) Indeed, there are other possibilities. Nodes could coherently cooperate, nodes could broadcast without the need for relays, etc. Among all the infinitely many strategies that one could envisage, which should one adopt for operating wireless networks?

In recent work [2] it is shown that if the signals undergo attenuation of at least a certain amount, then the multihop mode of operation is indeed order optimal.

Specifically, suppose that nodes are located on a plane with a distance of at least ρ_{min} separating nodes. Suppose also that the attenuation suffered by a signal over a distance ρ is $\frac{ce^{-\gamma\rho}}{\rho^{\delta}}$, and that all receptions are subject to additive i.i.d. white Gaussian noise, and all transmitters have a power constraint P_{ind}. Then it is shown that if either $\gamma > 0$, or $\delta > 3$, then the transport capacity of the network measured in bit-meters/second is $O(n)$, where n is the number of nodes. Moreover, in many situations, one can do load balancing through routing in such a way that the multihop mode of operation achieves this order of transport capacity. Consequently in such situations, multi-hop operation is order optimal.

This result should be compared with the previous result from [3] that under a interference limited model, the transport capacity of a network is $O\left(\sqrt{An}\right)$ where A is the area of the domain. Since in the model described earlier, nodes are a minimum distance $\rho_{min} > 0$ apart, the area grows at least like $\Omega(n)$, and so we find that the $O\left(\sqrt{An}\right)$ scaling law of [3] is actually information theoretically optimal.

The above discussion was for the case where the attenuation satisfied either $\gamma > 0$ or $\delta > 3$. In fact [4] develops a model based on photonic collisions, which appears to agree well with both measurements (in an urban Roman environment) as well as classical electromagnetics approaches. This analysis shows that generally one has $\gamma > 0$.

Indeed in such a case one can show that there is a fundamental bit-meter/joule bound on what a network can transport: If the total power available to all the transmitters combined is P_{total}, then irrespective of how it is allocated among the nodes, and what information is carried, and how nodes cooperate:

$$\text{Bit-meters/second transported by a network}$$
$$\leq cP_{total}.$$

The constant c, for which a formula is given in [2], is a fundamental bit-meters/joule constraint respected by wireless networks.

However one can also consider environments where $\gamma = 0$. What is the optimal strategy in such situations? The picture is known only partially. If $\gamma = 0$ and $\delta \leq \frac{3}{2}$, then it turns out that one can actually obtain unbounded bit-meters for a fixed number of joules. The strategy which achieves this is for the nodes to:

(i) Coherently cooperate: All upstream nodes use a portion of their power to coherently cooperate in getting a packet to its next hop.

(ii) Interference cancellation: A node cancels the interference from all known transmissions.

Thus we see that a new superior node of operation emerges in low attenuation scenarios; see [2].

Indeed it turns out that even in a network of nodes arranged on a straight line, one can obtain superlinear scaling of the transport capacity, i.e., $\Theta(n^\theta)$ for $\theta > 1$, when $\gamma = 0$ and $\delta < 1$.

We refer the reader to [2] for further details of these results.

2 Power Control

We now turn to the issue of protocols for multihop operation. Let us first consider the problem of power control. This is the problem of choosing the power level at which to transmit packets.

In [5] a protocol is developed for choosing an appropriate common power level for all nodes. This protocol is motivated by several considerations:

(i) A common power level facilitates the formation of bidirectional links, (though it does not guarantee them).

(ii) More specifically, the protocol tries to converge to the lowest common power level at which the network is connected. Such a strategy has been shown to be nearly optimal with respect to maximizing the network capacity in random scenarios in [3].

(iii) Choosing such a low power level is in conformity with power optimal routing which yields planar graphs (when $\delta \geq 2$).

This protocol, called COMPOW, allows an elegant software architecture for implementation. One can simply run several routing algorithms in parallel in user space, each operating at a different power level. Then the lowest power routing table giving connectivity to all the nodes is simply written into the kernel routing table. This protocol has been implemented on our network of Linux laptops [5].

The above protocol tries to choose a single transmit power level for all the nodes in the network that provides connectivity. As such it is hostage to the presence of even a few nodes which are further away from their neighbors. Thus one may desire to choose different power levels at nodes for different packets. Such a protocol, called CLUSTERPOW, has been developed in [6]. It simply looks up the routing tables at different power levels to see what is the lowest power routing table which contains the destination, and sends out the packet at that power level. It can be proved that this gives loop-free routes. It also has been implemented.

Yet another protocol, TUNNELED CLUSTERPOW, attempts to further whittle down the transmit power levels. It too is loop free; see [6].

A fourth protocol is MINPOW which simply attempts to minimize the total transmit power. An implementation is provided in [6] which does not require any physical layer support.

3 Media Access Control

The IEEE 802.11 protocol [7] uses an RTS-CTS-DATA-ACK handshake which silences the neighborhoods of both the transmitter as well as the receiver. It further employs backoff counters (and also carrier sensing).

This motivates the following question. Can one develop a protocol which makes reservations without making reservations, and one which does not silence the neighborhood of the transmitter? A protocol called SEEDEX has been designed in [8] for this purpose. It is a slotted protocol, where a node randomly chooses slots in which it will listen but not transmit, and others in which it may transmit. Such a random schedule is generated, and indeed determined, by the seed of the node's pseudo-random number generator. The idea of the SEEDEX protocol is for nodes to exchange their seeds by doing a fan-in and fan-out procedure during which the seeds get notified to exactly the two-hop neighborhood, which is exactly the source of the hidden terminal problems. Once these schedules are known, nodes can opportunistically, and also randomly, choose slots to transmit in. This protocol has been implemented. The main issue that needed to be resolved was a clock synchronization algorithm to enable slotted operation.

This protocol can be further modified so that it is used only in establishing the RTS-CTS part of the handshake, with DATA and ACK then being carried on reserved slots.

4 Routing towards a Wardrop Equilibrium

The Wardrop equilibrium from transportation theory (see [9]) is one in which packets (in our context) may utilize multiple paths, but the traffic flows are so allocated that the mean delay from a source to a destination is:

(i) The same along all utilized paths.

(ii) No lesser on any unutilized path than on the utilized paths.

One can make a case that this is a desirable objective, once one takes reordering delay for out-of-turn packet deliveries into account. The question is: Can one construct a distributed asynchronous algorithm that attains a Wardrop equilibrium?

This can be done by preferentially reducing the flow on higher delay routes and increasing it on lower delay routes according to an adaptation algorithm. The delays in turn are estimated by another iterative algorithm responding to acknowledgments as they are received. The net result is a two-time scale stochastic approximation algorithm that can be proved to converge in a certain Cesaro sense to a Wardrop equilibrium. We refer the reader to [10] for details.

5 Towards convergence of control with communication and computing

It appears that the next phase of the information technology revolution could well be the convergence of control with communication and computing. Technological enablers are the proliferation of embedded devices and low cost wireless connectivity. With each embedded device serving as a sensor or actuator, one has the possibility for a large control system orchestra interacting over the either.

A key question that arises is: What are the right abstractions, and what is the right architecture for the oncoming convergence?

It has been argued by Valiant [11] that the success of sequential computation is due to the von Neumann bridge. More generally, the architecture of the solution has played a very important role in the proliferation of technologies. For example, in communication, the source-channel separation architecture of Shannon has been at the heart of the digital revolution. In networks, the OSI architecture has allowed plug-and-play at all layers, and has thus enabled the massive proliferation of the Internet that we witness today. Similarly, the feedback architecture used in control has been spectacularly successful both in engineering as well as in biology.

Similarly, architecture is important for the oncoming convergence of control with communication and computing. This is being investigated in the Convergence Lab at the University of Illinois. The specific context consists of a fleet of cars, vision cameras, microcontrollers, and wireless networked laptops. The goal is to develop an architecture which is application independent and context independent. A preliminary step in the development of a software architecture for a "federated control system" is taken in [12].

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Biography

P. R. Kumar is Franklin Woeltge Professor of Electrical and Computer Engineering, and a Research Professor in the Coordinated Science Laboratory, at the University of Illinois, Urbana-Champaign. He obtained his B. Tech. degree from IIT Madras, and the D.Sc. degree from Washington University, St. Louis. He was the recipient of the Donald P. Eckman Award of the American Automatic Control Council. He has presented plenary lectures at the IEEE Conference on Decision and Control, the SIAM Conference on Optimization, the SIAM Annual Meeting, and the German Open Conference on Probability and Statistics, His current research interests are in wireless networks, the convergence of control with communication and computing, wafer fabrication plants, manufacturing systems, machine learning, and financial economics. He is a Fellow of IEEE.