Transmission Power Control in Wireless ad hoc Networks

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ABSTRACT

In ad hoc wireless networks, packets are relayed over multiple hops to reach their destination. In order to operate ad hoc networks several protocols, for media access control, power control, routing, and transport are needed. This work is concerned with conceptualization of the power control problem and exhibit a design situated at the network layer. Transmission power control is important because of the fundamental nature of the wireless network that is interference limited. Transmission power control has the potential to increase a network’s traffic carrying capacity, reduce energy consumption, and reduce the end-to-end delay. We start by postulating general design principles for power control based on the effect of transmit power on various performance metrics.

Key words- Network traffic, end-to-end delay, routing.

1. INTRODUCTION

A wireless ad hoc network is a decentralized network of nodes with radios, possibly mobile, sharing a wireless channel and asynchronously sending packets to each other, generally over multiple hops. The most notable characteristics of an ad hoc network are a lack of infrastructure, multihop communication by cooperative forwarding of packets, distributed coordination among nodes, dynamic topology, and the use of a shared wireless channel.

Medium access in ad hoc networks is a complex problem. Multiple access schemes popular in cellular networks are not easy to implement in ad hoc networks because of the need to dynamically allocate resources efficiently to allow spatial reuse. Dynamic assignment of frequency bands for FDMA, time slots for TDMA, or spreading codes for CDMA, are difficult because of node mobility and the consequent need to keep track of resources in a distributed fashion. Consequently, random access schemes where all nodes have anytime, anywhere access to the channel, have emerged as the preferred choice. In this model, simultaneous reception of two or more strong signals at the receiver is considered a collision. CSMA/CA is the principal medium access method adopted for a shared wireless channel. However, CSMA/CA does not solve problems associated with hidden terminals and exposed terminals, which have been tackled in MACA [1], and several extensions (see e.g., [2]), through a series of handshakes. The current industry standard for the physical layer and the link layer in wireless LANs and ad hoc networks, IEEE 802.11 [3], uses a combination of CSMA/CA and handshaking to solve the media access problem. IEEE 802.11 has been immensely popular for wireless LANs but its operation in ad hoc mode presents many problems. Still, it is currently the only choice if one is constrained to use commercial off-the-shelf equipment for ad hoc networking.

The wireless medium is an interference limited medium. Reducing the interference caused by various transmissions is critical for the efficiency and scalability of any wireless system. This motivates power control, which is a very complex problem for ad hoc networks. In cellular networks power control is a physical layer problem, where each transmitter adjusts its power level to achieve equal SNR at a common receiver that is the base station. A feasible choice of power levels exists for all the transmitters, and iterative algorithms exist to achieve the solution [4, 5]. Ad hoc networks
do not admit such a solution for power control, since there are many receivers, and in general it is not possible to simultaneously equalize SNR at several receivers. One goal of power control in ad hoc networks is to increase network capacity by increasing spatial reuse. Other possible goals are to save battery power and reduce end-to-end delay. Numerous approaches, for example [6, 7], attempt to perform power control at the MAC layer by adjusting the power level of every packet to guarantee an acceptable SNR at a given receiver, using feedback from the receiver. Another class of approaches, called topology control, vary transmit power at the network layer to favorably alter topology (since power decides range) according to certain metrics [8, 9]. There are other routing and media access schemes which focus on energy savings only, by using a variety of performance measures [9]. This spectrum of schemes traversing all the layers illustrates the complexity of choices regarding power control in ad hoc networks. Which layer does power control belong to? How does it impact the other layers? What is a suitable architecture for power control? These are questions that need to be answered if power control protocols are to be widely adopted.

The network layer provides the critical service of routing packets between remote nodes. The dynamic nature of ad hoc networks coupled with the lack of hierarchy makes routing very difficult in mobile ad hoc networks. However, many of the popular routing schemes, e.g., those which use the number of hops to the destination as the metric, do not work well even in static ad hoc networks. This is because the dynamic and interference limited nature of the wireless channel implies that the quality of links selected on a route is also important, and not just the number of links. Thus, the fundamental issue of selecting appropriate metrics for routing in wireless ad hoc networks is not yet well understood.

We have summarized above some issues related to the individual layers of the network stack. The architecture of the stack as a whole is also important. The popular TCP/IP stack for wired networks is often taken as the starting point for designing ad hoc networks. However, violating the layering often provides a performance improvement in wireless networks. This has led to the blooming field of cross-layer design. Keeping in mind the entirety of the network stack, these cross-layer proposals need to be carefully examined for their effects on various parts of the stack.

2. THE TRANSMIT POWER CONTROL PROBLEM

The wireless medium is a shared medium. Every transmission causes interference in the surrounding area. Successful reception of packets is possible only if this interference is within some limits. Thus, interference is a key feature of the wireless medium and fundamentally affects the traffic carrying capability of the wireless network. One of the effective mechanisms of controlling this interference is by controlling the transmission power. This motivates the transmit power control problem, which is the topic of this chapter.

The transmit power control problem in wireless ad hoc networks is that of choosing the transmit power for each packet in a distributed fashion at each node. We begin by making the case that power control is a challenging example of a design problem that cuts across several layers. The problem is complex since the choice of the power level fundamentally affects many aspects of the operation of the network: Any design of a power control protocol must also be vigilant to the effect it can have on other well-established protocols and the functioning of the associated layers. The reason is that the assumption of fixed power levels is so ingrained into the design of many protocols in the OSI stack that changing the power levels can easily result in their malfunctioning.

Transmit power control is therefore a prototypical cross-layer design problem affecting all layers of the protocol stack from physical to transport, and affecting several key performance measures, including the trinity of throughput, delay and energy consumption. Cross-layer design, in general, should be approached holistically with some caution, keeping in mind longer term architectural issues [10].

The first issue that arises is where in the network architecture should power control be located. Its resolution requires an appreciation of the issues involved at each layer. The second issue that arises is how exactly to
choose the power level. This solution needs to be
guided by its impact on multiple performance
measures, which in turn requires a theoretical
understanding of the impact of power control.
The final issue that arises is the issue of the
software architecture for the implementation. We
need to take into account the software
organization of the IP stack, and the interplay
between the kernel, user-space applications, and
the firmware on the wireless cards. The
solution also needs to be appropriately
modularized to allow future changes in routing
protocols without redesigning the entire power
control solution.
Given this complex web of interactions, we
begin by distilling a few basic design principles
to guide our design process for power control
[11]. Then we propose some protocols which
attempt to achieve several design objectives and
perform several optimizations simultaneously.
The COMPOW protocol [12] attempts to
increase network capacity, while meeting the
needs of several other layers by choosing a
common power level for use by all the nodes
throughout the network. The CLUSTERPOW
protocol [13] relaxes this constraint and
provides a joint solution to the power control,
clustering and routing problem, again with the
goal of maximizing network capacity. The
tunneled CLUSTERPOW protocol develops a
more sophisticated way of achieving a finer
optimization for network capacity, at the cost of
greater implementation complexity. The
MINPOW protocol achieves a globally optimal
energy consumption solution for awake nodes,
but may or may not increase network capacity
depending on the wireless hardware. The
LOADPOW protocol attempts to reduce end-
to-end delay by using higher power levels,
when the network load is low.
We also present software architectural designs
for cleanly implementing these protocols. We
have implemented COMPOW,
CLUSTERPOW, and MINPOW. Tunneled
CLUSTERPOW requires considerably more
implementation effort and was not implemented,
while LOADPOW could not be implemented as it
needs changes in the MAC protocol, which resides
in the firmware of the wireless card, which is not
accessible.
Experimental performance evaluations were
anyway not possible for any of the protocols
due to hardware limitations, which is essentially
designed for changing power levels at startup.
Thus, for quantitative comparisons we have also
implemented some of these protocols in the NS2
simulator, which interestingly turned out to
require more effort than the real
implementations in the kernel.
The rest of the chapter is organized as follows.
Section 2.1 describes and justifies a few design
principles for power control. The next five
sections describe the different power control
protocols, prove various properties and describe
the implementation of the protocols. Section 2.8
presents the simulation results in NS2 and
gives some details on the implementation of
the protocols in NS2.

3. DESIGN PRINCIPLES FOR POWER CONTROL

We begin our exploration by presenting
some design principles for power control.
I. To increase network capacity it is
optimal to reduce the transmit power
level. Any transmission causes interference in the
surrounding region due to the shared nature of
the wireless channel. The area of this interference
is reduced by reducing the transmission range, or
the power level. Low power levels, however,
result in a larger number of shorter hops, thus
increasing the relaying burden on a node. For
a transmission range of r, the area of the
interference is proportional to r^2, whereas the
relaying burden (i.e., the number of hops) is
inversely proportional to r.

Figure 3.1 A disk of area a m^2 containing nodes
The area consumed by a packet is thus
proportional to r (r^2 for 3-D networks),
implying that reducing the transmit power level
increases network capacity. This argument
holds fairly generally, and not just for the
asymptotic case when the number of nodes tends
to infinity. However, the argument does not hold for one-dimensional networks, where the capacity gains by interference reduction are exactly offset by the increased relaying burden.

We now present the above argument in a more quantitative form, simplified from [14] and also presented in [15]. Consider a domain of area $A = \pi r^2$, taken as a disk for simplicity of discussion, and containing $n$ nodes as shown in Figure 2.1. Suppose that each node can transmit at $W$ bits/s, and that the range of each node is $r$ meters. To model interference, let us simply suppose that for a node $R$ to successfully receive a packet from node $T$, it has to lie within a distance $r$ from $R$, and there can be no other simultaneous transmitter within a distance $(1 + \Delta)r$ of $R$. This model, called model, is depicted in Figure 2.2. The quantity $\Delta > 0$ captures the notion of allowing only weak interference. The protocol model is reasonably accurate for current wireless technologies like IEEE 802.11b, which employ carrier sensing.

Suppose source node has a destination node to which it wishes to send data at a rate of $\lambda$ bits/s. Suppose also that the average distance between a source and a destination is $L$ meters. The question we will investigate is: How does $\lambda$ vary with $r$?

Now let us examine how much can actually be transmitted. Consider two simultaneous transmissions, one from $T$ to $R$, and another from $T^0$ to $R^0$, as shown in Figure 2.2. For $R^0$ to hear $T^0$, we need $|T^0 - R^0| \leq r$ (where $|T^0 - R^0|$ denotes the distance between $T^0$ and $R^0$). On the other hand, to avoid interference we need $|T^0 - R| \geq (1 + \Delta)r$. From the triangle inequality, we see that $|T^0 - R^0| + |R^0 - R| \geq |T^0 - R| \geq (1 + \Delta)r$. Hence $|R^0 - R| \geq (1 + \Delta)r - |T^0 - R^0| \geq (1 + \Delta)r - \Delta r = \Delta r$. Thus, disks of radius $\Delta r$ around $R$ and $R^0$ are disjoint, as shown in Figure 2.3.

The interpretation is that each transmission “consumes” a “wireless footprint” of area.

Now, let us observe another important fact: Area is a valuable resource too in ad hoc networks, in addition to the shared radio spectrum. Note that the total area of the domain is $A = \pi r^2$. At least a fourth of the consumed area must lie in the domain even if the receiver is on the boundary of the domain, are simultaneously feasible.

![Figure 3.2](image-url) The protocol model of interference.

![Figure 3.3](image-url) Wireless transmissions consume area.

Due to the reciprocal dependence of the right hand side on $r$, decreasing $r$ increases the network capacity.

III. Reducing the transmit power level reduces the average contention at the MAC layer. Changing the range changes the number of one-hop neighbors that each node has and thus, the number of neighbors it has to contend with for media access. At the same time, changing the range changes the number of hops in a route and thus, the relaying burden that each node has to carry and consequently the amount of traffic that each node has to transmit.
The following argument shows that the net radio traffic in contention range is proportional to $r$, which is minimized by reducing $r$ [16]. The impact of power control on total energy consumption depends on the energy consumption pattern of the hardware.

IV. Power consumption for communication has three components: $P_{RX_{elec}}$, the power consumed in the receiver electronics for processing; $P_{TX_{elec}}$, the power consumed by the transmitter electronics for processing; and $P_{TX_{Rad}}(p)$, the power consumed by the power amplifier to transmit a packet at the power level $p$, where $p$ is the actual power that is radiated in the medium.

Also, define $P_{idle}$ to be the power consumed when the radio is on but no signal is being received, and finally, let $P_{Sleep}$ be the power consumed when the radio is turned off.

When the traffic load in the network is high, a lower power level gives lower end-to-end delay, while under low load a higher power gives lower delay.

At every hop a packet experiences processing delay, propagation delay, and queuing delay. Processing delay includes the time taken by the radio to receive the packet, decode it, and retransmit it if necessary. Propagation delay is the time taken by the radio waves to travel the physical distance separating the nodes. Queuing delay is the time spent by the packets waiting in the queue of the forwarding nodes because the medium is busy. The end-to-end delay for a packet is the sum of the delays it experiences at every hop. Processing delay grows approximately linearly in the number of hops and is thus inversely proportional to the range.

Queuing delay depends on the accessibility of the medium, i.e., on the MAC contention and the interference in the neighborhood. Since contention increases linearly with the range, queuing delay increases superlinearly with the power level, given the convex dependence of delay on load. Power control does not affect the propagation delay much, as it depends only on the end-to-end distance. Thus a higher transmit power implies higher queuing delay, whereas a lower transmit power implies higher processing delay.

Whether the processing delay or the queuing delay dominates depends on the network load. Under low load, queuing delay is insignificant, and thus, it is beneficial to use a higher transmit power which reduces the processing delay. On the other hand, when the network load is high, queuing delay dominates, and it is desirable to use a low transmit power to reduce the total end-to-end delay. This is qualitatively indicated in Figure 2.7. An ideal power control protocol should follow the troughs of these curves. To verify our predictions and to get an estimate of the cross-over points, we simulated a topology of 80 nodes placed randomly in a $1000 \times 500$ m rectangular grid, using the NS2 simulator.

The MAC protocol used was IEEE 802.11b and the routing protocol was DSDV. The network load was varied by increasing the number of randomly selected source-destination pairs which carried constant bit-rate UDP traffic. As seen in Figure 2.8, a lower power level can sustain more traffic since it blows up later than a higher power level curve. However at low loads, a higher power level gives a lower delay. The delay jitter also shows a similar trend.

V. Power control can be regarded as a network layer problem.

This is a central thesis of our approach to power control. Power control impacts multiple layers.
of the network stack, including the physical, the data link, and the network layers. Numerous approaches (e.g., [6, 7]) attempt to solve the power control problem at the MAC layer. The strategy is to adjust the transmit power level of every packet such that the SINR at the intended receiver is just enough for decoding the packet. The claim is that this minimizes interference as well as saves energy. One point to note, though, is that the intended receiver is determined by the network layer (i.e., by the routing table entry) and not by the MAC layer. The job of the MAC layer is only to transmit the packet to the receiver specified by the higher layers. Thus, placing power control at the MAC layer does not give the routing protocol the opportunity to determine the optimal next hop or the intended receiver. In other words, the MAC approach to power control only does a local optimization whereas network layer power control is capable of a global optimization. When the power level used by a node changes slowly compared to routing updates, power control can be viewed as the “topology control” problem. A more tight coupling of routing and power control can be effected by per-packet power control, which enables us to solve the clustering problem also in a clean way along with the power control problem, as we will see in the sequel. Thus, we argue for power control to be properly situated as a network layer protocol. The above is only a guiding principle. In order to solve the power control problem, we need to show how it can be solved at the network layer resolving all the issues that we have raised. Some solutions may need help from other layers and one may resort to cross-layer design.

**CONCLUSION**

In this work, we identify and address several problems in protocol design for ad hoc networks. This dissertation takes a pragmatic yet principled approach to designing and building ad hoc networks. The problems are approached in a holistic manner. The protocols we develop are implemented and tested in real systems to the extent possible. This ensures that due importance is given to both system and software architecture. Contributions are made in the form of design principles, protocols, and implementations in real systems, simulational and experimental studies, architectural suggestions for the stack as a whole, and several tools and libraries.

**REFERENCES**


