Load-Sensitive Transmission Power Control in Wireless Ad-hoc Networks

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***Abstract*— Transmission power control in ad-hoc networks has hitherto been used only for achieving network connectivity. It has been implicitly assumed that the optimal throughput performance in ad-hoc networks can be achieved when using the minimum transmission power required to keep the network connected. However, in this paper we argue that such an assumption remains valid only under high node densities not characteristic of typical ad-hoc networks.**

Using both throughput and throughput per unit energy as the optimization criteria, we demonstrate that the optimal transmission power depends on several network characteristics such as the number of stations, the network grid area, and the traffic load. In particular, we show that the optimal power is a function of the network load for *typical network scenarios*. Finally, we propose two transmission power control algorithms called Common Power Control(*CPC*), and Independent Power Control(*IPC*) that adjust the transmission power adaptively, based on the network conditions to optimize throughput performance. Simulation results show that both adaptive power control algorithms achieve better throughput per unit energy than constant power control.

I. Introduction

In this paper, we investigate the transmission power adjustment problem in ad-hoc wireless networks. The transmission power of the stations in a network determines the network topology, The transmission power of the stations in a network determines the network topology, and hence can be shown to have a considerable impact on the throughput of the network and the energy consumption of the stations. There exist several related works [1], [2], [3] that have either implicitly or explicitly addressed the problem of transmission power adjustment in ad-hoc networks. [1] and [2] propose schemes to determine in a distributed fashion the transmission power that would minimally connect the network. [3] explicitly argues for operating the stations with the minimum transmission power that would keep the network connected.

In this paper, however, we argue that the minimum transmission power will not always deliver the maximum throughput in typical mobile ad-hoc networks (consisting of a few hundred of nodes distributed over an area of few square miles). We demonstrate that the optimal transmission power is determined by the *network load*, the *number of stations*, and the *network grid area*. Furthermore, for a typical ad-hoc network with a given number of stations and network area, we show that the optimal transmission power becomes a function of the network load. We substantiate these arguments through a comprehensive set of simulation results.

To attain the optimal topology that achieves maximum throughput per unit energy, we present two adaptive power control schemes called Common Power Control *(CPC)* and Independent Power Control *(IPC)*, that adapt the transmission power based on the dynamic network conditions. In CPC, all nodes are forced to use the same transmission power. Hence, such an approach can be easily adopted in tandem with existing ad-hoc network protocols that assume common power usage. On the other hand, we also propose the IPC approach that allows nodes to use independent transmission powers. IPC operates in a purely distributed fashion and requires no global coordination to synchronize the transmission powers as in CPC. We evaluate the proposed schemes and compare their performance against static schemes using minimum and maximum transmission powers.

The rest of the paper is organized as follows: Section II describes the simulation environment. Section III presents the simulation results that motivate the load sensitivity of optimal transmission power. Section IV proposes two adaptive transmission power control algorithms that optimize throughput per energy performance. Section V concludes the paper.

II. Simulation Model

A. *ns2 Simulatioin Environment*

The wireless physical layer in *ns2* is based on the IEEE 802.11 DSSS specifications. The signal propagation model used is a combination of the free space propagation model (for distances less than 100m) and the two-ray ground reflection model (for distances greater than 100m) [4]. The data rate of the underlying channel is 2Mbps. We use constant bit rate traffic over UDP in all the simulations. The packet size is set to 512 bytes. Source destination pairs are randomly chosen from the network stations. The IEEE 802.11 protocol in the distributed coordination function mode is used at the MAC layer. Dynamic source routing (DSR)[5] is used as the routing protocol. The transmission range is varied from the minimum range required to keep the network connected to the maximum range required to make the network fully connected. Only static networks are used in the simulations.

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B. Energy Model

We classify power into three different components; transmission power required to send data, receive power required to receive or listen to data, and idle power required to wake up. Transmission power includes both the power required to drive the circuit and the transmission power from the antenna. The power required to drive the circuit is set to 1.1182W, while the transmission power from the antenna is computed based on the distance between sender and receiver using the two-ray ground reflection model, and is equal to $(7.2 * 10^{-11} * d^4)$W for a transmission distance of d meters. The receive and idle power values are assumed to be 1W and 0.83W respectively [6].

C. Metrics

We use the following metrics for the simulation results: (a) per-flow throughput measured in Kbps, (b) per-flow throughput per unit energy measured in bps/W, (c) spatial re-use factor measured as the average number of simultaneous transmissions occuring per transmission slot during the simulation, (d) average path-length per flow measured in hops, and (e) average contention time per packet, measured as the sum of transmission time and backoff time due to collision. We also measure IEEE 802.11's utilization of a mini-channel's[1] capacity (measured in Kbps) as the number of contending flows increases. We then use the utilization curve in our reasoning of the other results observed.

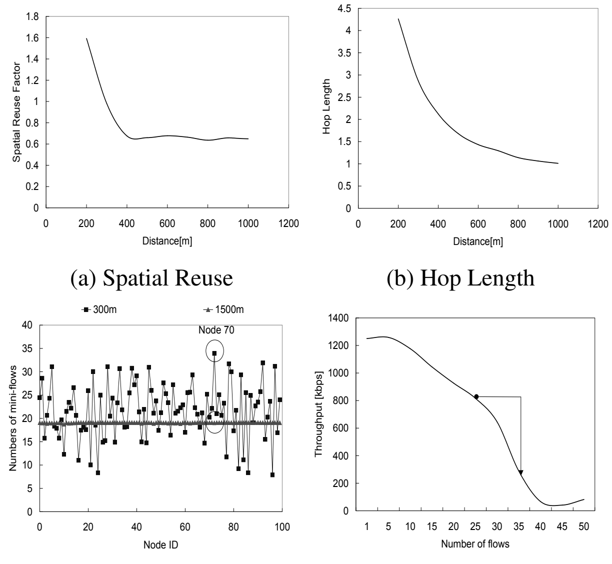
III. Observation using Constant Power Control

This section evaluates a constant power control scheme without adaptation, and thus motivates the need for adaptive power control. We begin by considering a typical ad-hoc network environment with a fixed network size and a fixed number of nodes, but observe the performance as the network load changes. In [7], we present more extensive results for other network scenarios including (a) fixed traffic load, variable number of nodes, and fixed network size, and (b) fixed traffic load, fixed number of nodes, and variable network sizes.

A. Preliminary Observations

We identify the three key factors that influence throughput performance in an ad-hoc network to be: the *degree of spatial re-use*, the *average hop length*, and the *contention in the network*. However, we observe that the lack of (or minimal) spatial re-use in typical ad-hoc network configurations is the cause for the pronounced load sensitivity of the optimal transmission power.

Figure 1(a) and (b) show the spatial re-use factor and average hop length, as a function of various transmission distances used by mobile nodes. Figure 1(c) shows the number of flows which contend with each other at each mobile node for two different transmission distances. In addition, Figure 1(d) presents IEEE 802.11's utilization as a function of the number of contending flows.



(a) Spatial Reuse (b) Hop Length

(c) Contending Flows (d) Utilization vs. Flows

Fig. 1. 1000m by 1000m area, 100 nodes, 15 flows, 60Kbps

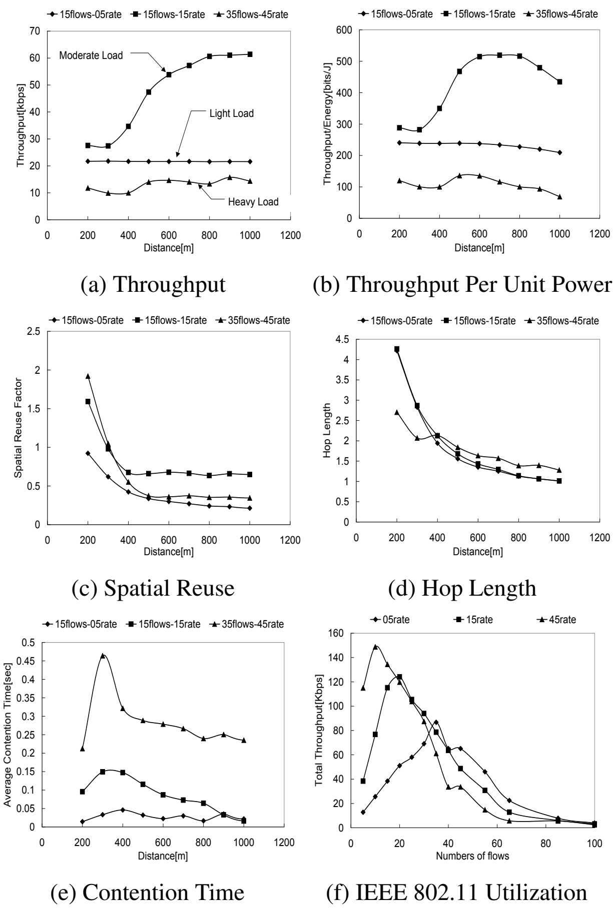
Nine different scenarios are used to produce the results of Figure 1. Each scenario consists of 100 mobile stations distributed randomly in a 1000m by 1000m network grid and 15 flows with each flow sending at a constant bit rate of 60Kbps[2]. It is evident from Figure 1(a) that the ratio of the spatial re-use factors at the minimum and maximum transmission ranges is merely 2:1. On the other hand, the average hop-length ratio is around 4:1. Also, most interestingly, the number of contending flows in Figure 1(c) increases with a decrease in transmission range. This is because of the multiple hops of each end-to-end flow contending with each other and effectively increasing the number of contending flows for any portion of the underlying channel.

For example, the node with ID 70 in Figure 1(c) experiences the maximum contention (35 mini-flows[3]) among all the nodes when a transmission range of $300m$ is used. On the other hand, the maximum contention in the case of the $1500m$ transmission range is among 20 mini-flows. The corresponding utilization curve for IEEE 802.11 shows that when each flow is sending data at 60Kbps, a change in the number of mini-flows from 20 ($1500m$, maximum transmission range) to 35 ($300m$, min transmission range) lowers the utilization at the MAC layer by around 65%. This simple example illustrates that using a minimal transmission range might not always optimize throughput performance.

[1] We define mini-channel as an area where atmost one transmission can occur because all nodes within mini-channel are within range of each other.

[2] We refer to the load of 15 flows as moderate traffic load.

[3] We define a mini-flow as a one-hop transmission.



(a) Throughput (b) Throughput Per Unit Power

(c) Spatial Reuse (d) Hop Length

(e) Contention Time (f) IEEE 802.11 Utilization

Fig. 2. Various load, fixed number of nodes, fixed network size

B. Impact of Traffic Load

Figure 2 shows the results observed when the number of nodes and grid size are fixed at 100 and 1000m by 1000m respectively. Three different loads of 5 flows, 15 flows, and 45 flows respectively are used (with each flow having a data rate of 60Kbps). From Figure 2(a), it can be observed that (i) for the lightly loaded scenario, the maximum throughput (per-flow) is achieved at the low transmission range of 300m, (ii) for the moderately loaded scenario, the maximum throughput (again per-flow) is achieved at a transmission range of approximately 800m, and (iii) for the heavily loaded scenario, the utilization is poor and the maximum throughput is achieved approximately at 1000m (the throughput curve is relatively flat for this scenario and close to maximum throughput is achieved even at 500m).

This illustrates the fact that for a given topology, the optimal transmission range (in terms of throughput performance) is variable and is a function of the load in the network.

We also present the throughput per unit energy results for the scenarios in Figure 2(b). The peaks of this result are at 300m, 800m, and 500m for the lightly loaded, moderately loaded, and heavily loaded scenarios respectively.

We now explain the reasons behind the throughput and throughput per energy consumption results observed using Figures 2(c), 2(d), and 2(e). The spatial re-use factor stays below 2 for all scenarios while the hop-length goes up to 4 for the minimal transmission range. A more revealing result is the contention time or the time taken to successfully send a packet. This metric is a direct measure of the number of flows contending for any portion of the channel and hence is indicative of the utilization achieved at the MAC layer. The curve for the moderately loaded scenario shows a peak at around 300-400m indicating lower utilization and thus explaining the lower throughput at those transmission ranges. The adaptive transmission power algorithms that we present in Section IV are based on *achieving the lowest contention time possible in the network.*

IV. LOAD-SENSITIVE POWER CONTROL

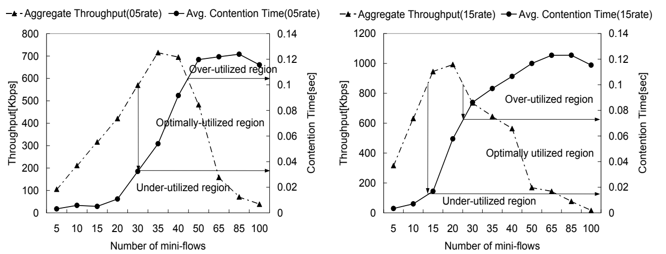
In this section we first present a basic scheme to control power adaptively, based on changes in the network load. We then use the basic scheme to describe two load-sensitive transmission power control algorithms: (i) Common power control (CPC) that forces every node to use same transmission power, and (ii) Independent power control (IPC) that allows every node to independently decide its transmit power. The performance of the proposed schemes is evaluated using dynamic load environments.

A. Assumptions

Although, in Section III, spatial re-use, hop-length, and contention levels are portrayed as the key factors affecting the optimal transmission range, based on the results presented, it can be observed that for moderately sized networks, spatial re-use and hop-length factors are compensative in nature, and hence counter-balance each others' impact. The impact of spatial re-use starts to outweigh that of the hop-length for larger (and hence atypical) network sizes. Furthermore, the effects of spatial re-use and hop-length can be captured more deterministically given the network grid area and the number of nodes[7]. Hence, the *CPC* and *IPC* schemes are primarily based on the dynamic monitoring of the contention time observed at each node in the network.

B. Contention Time Thresholds

To estimate the traffic load, every node uses two thresholds for contention time; (i) α is a lower bound for optimally utilized region and (ii) β is a upper bound for optimally utilized region. The thresholds are chosen to maximize the throughput for different kinds of traffic loads. Figure 3(a) and (b) show the optimal points for the thresholds for different data rates. It can be seen that throughputs above 80% of the maximum throughput are located when the contending number of mini-flows is between 30 and 50 (labelled as the optimally utilized region). Corresponding to 30 and 50 mini-flows, the contention times happen to be 0.02 and 0.1 seconds respectively. Therefore, to utilize the capacity of network optimally, the contention time has to be between 0.02 and 0.1 seconds. We empirically choose



(a) 5 packets/sec (b) 15 packets/sec

Fig. 3. Background for Contention Time Thresholds: Throughput and Contention Time

(from the extensive simulation results) 0.008 and 0.1 seconds as the lower threshold α and upper threshold β, respectively. We describe how α and β are used next.

C. Basic Mechanisms

Fundamentally, the two versions of power control schemes presented later use the same basic procedure to monitor contention time, and determine the nature of adaptation:

1) Measuring Contention Time: Each node observes the contention time over a period of T seconds which is referred as an *epoch*. While a smaller T will enable quicker power adaptation to changes in the environment, the trade-off is of-course the stability of the algorithm. We empirically set T to one second.

2) Increasing Transmission Power: If a node detects the measured contention time to be above the upper threshold β, it increases the transmission power in order to decrease the number of contending mini-flows in the surrounding mini-channel. The corresponding improvement in utilization would in turn improve the throughput performance.

3) Maintaining Transmission Power: If a node observes the measured contention time to be within the range between β and α, it maintains the transmission power in order to continue utilizing the capacity of the channel optimally.

4) Decreasing Transmission Power: However, if a node observes the measured contention time to be below the lower threshold α, it should decrease the transmission power to increase the number of contending mini-flows which go through the node. Note that although the end-to-end throughput would remain the same after this phase, the energy consumption would reduce thus improving the throughput per energy performance.

D. Common Power Control Scheme

Because general ad-hoc networks assume the symmetric links and routes, we propose the common power scheme which guarantees symmetric links and routes. In CPC, all nodes in the network use the same transmission power. After each node independently uses the basic mechanisms outlined earlier to determine the optimal transmission power, the only largest power is chosen by all nodes with a flooding method.

1) Transmission Power Advertisement: After observing the contention time, and deciding the power with the basic procedure, each node advertises it's transmission power to the other nodes by flooding an advertisement for the transmission power. The flood forward mechanism at intermediate nodes is set up so that messages which carry a smaller advertised value than that of earlier forwarded messages within the same epoch, are suppressed to decrease the overhead of flooding. Note that while network floods performed using series of local broadcasts can induce the broadcast storm problem[8], other mechanisms such as [9] can be used to alleviate some of the overheads.

2) Route Recomputation: Once all nodes agree to the largest transmission power, the next step is to recompute new routes for the flows because of the altered topology. In case of an increase in transmission power, some flows can experience path shortening. The dynamic source routing (DSR) protocol is already equipped with such a *route optimization* mechanism that will detect shorter routes and update the concerned source accordingly. However, in case of a decrease in power, some flows can suffer link failures. While mechanisms could conceivably be developed to perform *route lengthening* in an optimal fashion, we rely on DSR's route recomputation process to recover from such failures.

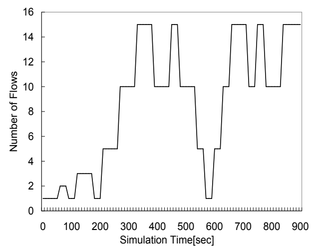
E. Independent Power Control Scheme

Because of the inherent overheads involved in global coordination, it is desirable for the ideal power control scheme to support distributed coordination among nodes. IPC allows each node to use it's own transmission power. However, because two neighboring nodes may use different transmission powers, some links will becomes asymmetric unlike in conventional adhoc networks. While several recently proposed protocols tackle the presence of asymmetric links at the routing layer [10], [5], the possibility of wide-spread proliferation of asymmetric links will also necessitate changes at the MAC layer.

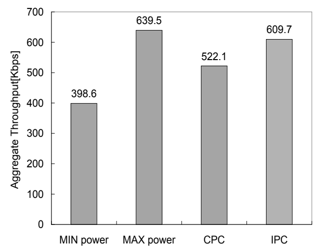
1) Extending IEEE 802.11 for Asymmetric Links: In the conventional IEEE 802.11 MAC, a sender transmits an RTS, and DATA packets to a receiver, and the receiver responds with CTS, and ACK packets to the sender. Because the MAC layer uses the same power for all packets, asymmetric links will induce link failures. If the receiver, however, uses the power notified by the sender (say piggybacked on the RTS packet) to transmit CTS and ACK packets, asymmetric links can be supported successfully. While this will increase the header overhead by about one byte, it is a negligible increase[4].

2) Asymmetric Routes and DSR: Although sophisticated routing schemes could potentially be used to use asymmetric routes, such mechanisms are outside the scope of this paper. For our simulations, we restrict the route selection process to choose only symmetric routes by sending back DSR route-replies along the route the route-request traversed through.

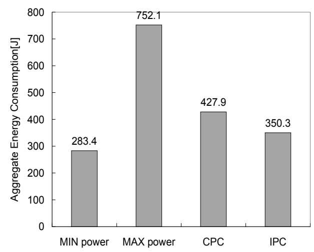
[4]The default sizes of RTS, CTS, DATA, and ACK packets in ns2 are 35 bytes, 28 bytes, 512 bytes, and 28 bytes, respectively.



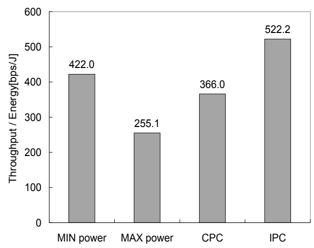
(a) Load Scenario



(b) Throughput



(c) Energy Consumption



(d) Throughput per Unit Energy

Fig. 4. Scenario, and Results of Simulation

F. Performance Evaluation

1) Basic Scenario: To evaluate the performance of the proposed algorithms, we have implemented the algorithms in *ns2*. We simulate nine different samples, and the environment consists of 100 nodes randomly distributed in an 1000m by 1000m area. Each simulation uses varying traffic loads with the number of flows randomly changing from one to fifteen during the simulation. The simulation time is 900 seconds and the number of flows at any given point in time is shown in Figure 4(a). The data rate of each flow is 60Kbps.

2) Comparisons: In the rest of the section we evaluate the proposed algorithms and compare their performance with the *minimal constant* transmission range algorithm (*const-300m*), and *maximal constant* transmission range algorithm (*const-1500m*). *const-300m* uses the minimum possible transmission range so that the each network of nine different samples remains connected. *const-1500m* uses the transmission range required to make the network fully connected.

Figure 4(b), (c), and (d) show the performance of the *CPC* and *IPC* algorithms for a scenario in which the load in the network dynamically varies. Since the load on the network changes dynamically, the transmission range used by the stations in the network is also changed based on the proposed algorithms.

Figure 4(b) shows the averaged aggregate throughput for the nine simulation runs for the *const-300m*, *const-1500m*, *CPC*, and *IPC* algorithms respectively. It can be observed that the throughput of *const-300m* is the lowest when compared to the others. *const-1500m* enjoys the best throughput possible because of the lightly to moderately loaded conditions used. The CPC has a lower throughput than that of IPC because of the flooding overhead. Although IPC does not have a centralized scheme to coordinate individual transmit powers, and no sophisticated support for asymmetric routes, it achieves slightly lower throughput than that of the maximum power transmission.

Although *const-1500m* has the highest throughput, it consumes the largest energy as shown in Figure 4(c). Both the proposed algorithms consume much less energy than the maximum power case. IPC, especially, performs the best in terms of the throughput per energy performance, notwithstanding the fact that its performance can further be improved by providing asymmetric route support. Consequently, we believe that the results presented in Figure 4 stand as a proof of concept that motivates load-sensitive algorithms that adapt the transmission range based on the traffic load conditions.

V. CONCLUSIONS

Under typical multi-hop network scenarios, we show that the optimal transmission range is a function of the load in the network. We present two transmission power control algorithms called common power control (CPC), and independent power control (IPC) that adaptively change the transmission power used by stations in the network based on the load conditions. In CPC, all nodes in the network use the same transmission power. While this prevents the algorithm from achieving the optimal throughput per unit energy, it renders CPC more suitable for environments where the protocols rely on common power being used by nodes in the network. On the other hand, in IPC, nodes potentially use independent transmission power resulting in optimal throughput per unit energy.

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