Quantitative Analysis of Transmission Power Control in Wireless Ad-hoc Networks

Seung-Jong Park and Raghupathy Sivakumar
School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, GA 30332, USA
sjpark@ece.gatech.edu and siva@ece.gatech.edu

***Abstract*—In this paper, we address the issue of transmission power control in wireless ad-hoc networks. In general, it is assumed that minimum transmission power achieves the optimal throughput of an ad-hoc network because it produces minimum interference. However, this assumption can be realized under high node density which is not typical. Therefore, we show that using the minimal transmission range might not *always* results in optimal throughput performance. Using both throughput and throughput per unit energy as the optimization criteria, we demonstrate that the optimal transmission power is generically a function of the number of stations, the network size, and the traffic load. In particular, we observe that the optimal power is a function of the network load for *typical network scenarios*. To analyze these observations, we define an analytical throughput model using three factors: spatial re-use, hop count, and contention time. The throughput model supports the results of observations; throughput is proportional to transmission power in typical ad-hoc environments. Consequently, we conclude that the transmission power should be adjusted to the environment of ad-hoc networks in order to maximize the throughput performance.**

I. INTRODUCTION

Ad-hoc networks are multi-hop wireless networks with applications in military environments, sensor networks, disaster relief operations, and zero-configuration networks [1]. Since ad-hoc networks typically lack the services of dedicated routers, the mobile stations that form the ad-hoc network also act as routers.

Because ad-hoc networks do not require an infrastructure, they have been attractive to military and emergent environments. Recently, they are also expected to expand the application into commercial areas: laptop, personal digital assistant (PDA), and mobile phone.

In this paper, we investigate the transmission power adjustment problem in ad-hoc wireless networks. In general, the topology of an ad-hoc network is determined by the transmission power of the stations. Because different topologies have different throughputs, the transmission power can have a considerable impact on the throughput of the network and the energy consumption of the stations. There exist several related works [2], [3], [4], [5] that have either implicitly or explicitly addressed the problem of transmission power adjustment in ad-hoc networks. [2] and [3] propose schemes to determine in a distributed fashion the transmission power that would minimally connect the network. [4] explicitly argues for operating the stations with the minimum transmission power that would keep the network connected.

In this work, we argue that, for typical mobile ad-hoc networks [6] (consisting of a few hundred of nodes distributed over an area of few square miles), the minimal transmission power will not always deliver the maximum throughput. We demonstrate that the optimal transmission power is determined by the *network load*, the *number of stations*, and the *network size*. Furthermore, for a typical ad-hoc network with a given number of stations and network density, 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 in both typical and atypical network configurations in terms of number of stations and network density. To prove our argument, the analytical throughput model is derived as a function of transmission power and we show that throughput increases as the transmission power increases in typical ad-hoc environments.

The rest of the paper is organized as follows: First, section II presents recent related works which propose power control schemes in ad-hoc networks. Section III describes the terminology, which is used in the rest of the paper. In Section IV we describe the simulation environment and present the simulation results that motivate the load sensitivity of optimal transmission power. Section V presents the analytical model of throughput derived from three influential factors to analyze the observations in section IV. Finally, in Section VI, we conclude the paper.

II. RELATED WORKS

In [2], the authors propose two algorithms to adjust the transmission power to create two desired topologies: connected and biconnected networks through centralized and distributed methods. The results of the experiments show that connectivity and biconnectivity improve the throughput and power consumption significantly. We, moreover, consider throughputs of other connectivities when mobile nodes use larger power than that of (bi)connectivity.

[3] proposes a distributed power control algorithm based on directional information. Each node increases transmission power until it finds a neighbor node in every cone of angle α, where $\alpha <= 2 * \pi/3$ to guarantee maximum connected node set theoretically. The resulting network topology increases network lifetime by reducing transmission power and reduces traffic interference by having low node degrees. In our study, we focus on both throughput and throughput per unit energy.

[4] conceptualizes the power control problem, and provides a protocol which suggests that low common transmission power maximizes throughput capacity, extends the battery life, and reduces the contention at the MAC layer. Although their suggestion is true in a general sense, we show that the low common transmission power cannot always provide the optimal throughput in typical ad-hoc environments.

In [5], the authors study the effects of transmission range on AODV's multicast performance at varying transmission ranges. They show that increasing the transmission range has pros and cons toward the AODV's multicast environment; they conclude that the transmission range should be adjusted to meet the targeted throughput while minimizing battery power consumption. The analytical throughput model in our paper, furthermore, proves that the optimal transmission range should be adjusted to environments such as traffic load, node density, and network size.

In [7], the authors propose a power control method at the MAC layer that finds the lowest power level between two communicating stations in order to reduce total interference which can reduce the capacity of the wireless network. After topology is fixed by constant power, their method increases throughput by reducing interference. We, moreover, show that the throughput can be also improved by changing topology with adaptive power.

III. TERMINOLOGY

Before describing the observations, we define the terminology, which is required to explain phenomena in the simulations. In an ad-hoc network, three factors are considered to explain the throughput: spatial re-use, hop count, and contention time. Because, in this work, we use the

IEEE 802.11 medium access control (MAC) protocol, which is a carrier sense multiple access/collision avoidance (CSMA/CA) protocol, some factors can be influenced by the IEEE 802.11 MAC protocol.

A. *Typical Ad-hoc Network*

Generally, ad-hoc networks consist of several hundreds of mobile nodes. Therefore, most papers [2], [4], [8] about ad-hoc networks assume environments, which have less than 1,000 mobile nodes and is smaller than 10,000m X 10,000m area. This paper pays attention to the commercial or military ad-hoc environment, which consists of several hundreds of mobile nodes. And this work refers it as a *typical ad-hoc network*.

B. *Hop Count*

Because an ad-hoc network is infrastructureless, a source node of a flow should traverse several intermediate nodes to reach a destination node. A hop is a link between two nodes which communicate to each other directly; hop count is defined as the number of hops between the source and the destination of flows. The number of hop count is basically determined by a routing scheme, which decides the best route from a source to a destination. In general, most routing protocols choose the shortest route, which has the smallest number of hops. Because the transmission range changes the length of one hop, transmission range also changes the number of hops. As hop count increases, the total time to reach a destination increases. For that reason, hop count can impact on the performance of ad-hoc networks.

C. *Mini-channel*

In general, because channel access schemes for ad-hoc networks are based on contention, only one node is allowed to send data within a special region, which is called a mini-channel, to prevent nodes from colliding. The mini-channel is a region where only one node can transmit data and the others should wait. If a sender uses a channel, the neighbors located within the first hop cannot use a same channel simultaneously. Moreover, because this paper assumes ad-hoc networks using CSMA/CA to solve a hidden terminal problem, other nodes located at the second hop, cannot use the same channel as in Figure 1.

D. *Mini-flow*

To describe the contention within mini-channel, this paper refers one hop between two nodes as a mini-flow. Therefore, mini-flows from source node to destination node comprise a flow in ad-hoc networks.

E. *Spatial Re-use*

The spatial re-use is presented by spatial re-use factor, which is defined as the number of simultaneous transmissions per a transmission slot. It is measured in the total number of transmissions divided by the total number of transmission slots. Conceptually, it is considered as the number of mini-channels.

F. *Contention Time*

As the nature of contention-based MAC protocol, Each node should wait until a mini-channel is free. Therefore, the time for each transmission of packets consists of back-off time to wait and transmission time to send a packet. A contention time is measured in the total time including back-off time to wait until sensing free channel and transmission time to send a data based on bandwidth.

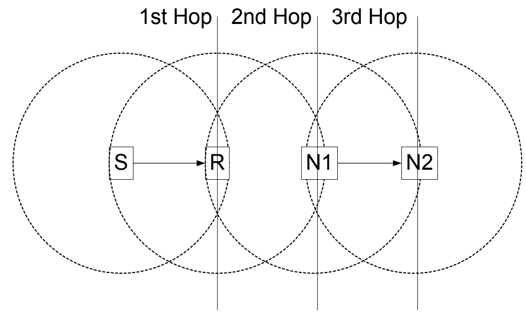


Fig. 1. Illustration of a mini-channel; nodes located within the second hop cannot send data

G. *Utilization of 802.11 DCF*

We define the utilization as the total throughput of mini-channel as a function of the number of mini-flows to find the optimal number of flows under given ad-hoc environments. To maximize the total throughput of network, each utilization of mini-channel should be maximized. Therefore, the utilization is the important measure to check the status of network capacity.

IV. OBSERVATIONS ON CONSTANT TRANSMISSION POWER CONTROL

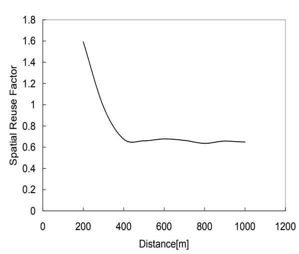
In this section, a preliminary result of simulation under the typical environment will be shown to motivate adaptive power control of an ad-hoc network. Thereafter, three scenarios will be extended to generalize the motivation: (a) various traffic load, constant number of nodes, and fixed network size, (b) fixed traffic load, various number of nodes, and fixed network size, and (c) fixed traffic load, constant number of nodes, and various network size. At the end of the section we discuss the observed results and present some simple relationships between throughput and the factors studied.

A. *Simulation Model*

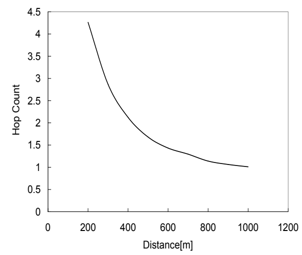
We use the network simulator 2 (*ns2*) [9] for all the simulations. In the rest of the section we describe the simulation parameters used and details of the metrics measured.

1) ns2 *Environments:* The physical layer of *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 the distances of less than 100m) and the two-ray ground reflection model (for the distances of greater than 100m) [10]. The data rate of the underlying channel is 2Mbps. Although TCP is used widely, constant bit rate (CBR) traffic over UDP was used in all simulations to simplify analysis of performance[1]. to simplify analysis, we use static network where all nodes do not move in the simulation. The size of the payload of a packet 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)[10], [11] is used as the routing protocol. DSR uses source routes rather than independent hop-by-hop routing decisions made by each node that forwards packets. In DSR, each packet carries the complete, ordered list of nodes through which the packet must pass. The transmission range is varied from the minimum transmission range (around 250m for the default topology) required to connect the network, to the maximum transmission range set to connect the network *fully*.

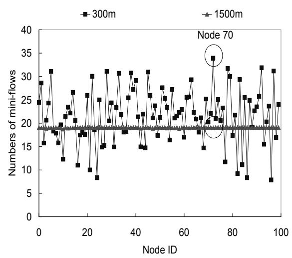
[1] We also have done simulations using TCP as the transport protocol and have observed very similar results as those of UDP



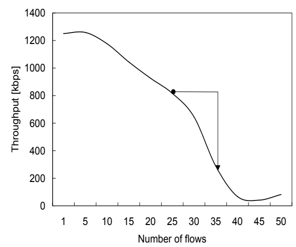
(a) Spatial Reuse



(b) Hop Count



(c) Contending Flows



(d) Utilization vs. Flows

Fig. 2. Simulation Results for Basic Scenario(1000m by 1000m Network Size, 100 Nodes, 15 Flows, 60Kbps)

2) Energy Model: To emulate a realistic environment, we measure power by monitoring three kinds of powers; transmission power required to send a packet, reception power required to receive or listen to a packet, and idle power required to stay awake. Transmission power includes both the power required to drive the circuit and the transmission energy from the antenna. The energy required to drive the circuit is set to 1.1182W [8],while the antenna transmission energy is computed based on the transmission range 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 [8]. The receiving and idle power values are assumed as 1W and 0.83W respectively [8].

3) Metrics: We present the following metrics for all the simulation results: (a) Per- flow throughput measured in Kbps, (b) Per-flow throughput per unit energy measured in bps/Watt, (c) Spatial re-use factor measured in number of different transmissions occurred at the whole area simultaneously (d) Average hop-count per flow measured in hops, (e) Contention time measured as average time taken to send a packet, and (f) utilization of the capacity of a mini-channel measured in an aggregate throughput when all flows contend with each other (because network is fully connected).

B. Preliminary Results

We identify the key factors that influence throughput performance in an ad-hoc network to be the *spatial re-use*, *hop count*, and *contention in the network*. We then show 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 2(a) and (b) show the spatial re-use factor, average hop count, as a function of varying transmission distance between mobile nodes. Figure 2(c) shows the number of flows which contend with each other at each mobile node for different transmission distances. In addition, Figure 2(d) presents IEEE 802.11's utilization as a function of the number of contending flows.

The scenario consists of 100 mobile stations distributed randomly in a 1000m X 1000m network size and 15 flows with each flow transmitting at a constant bit rate of 60Kbps[2] Each data point is averaged over 9 samples and results are shown only for connected scenarios. It

[2]In this work, we refer to this traffic as the moderate traffic load

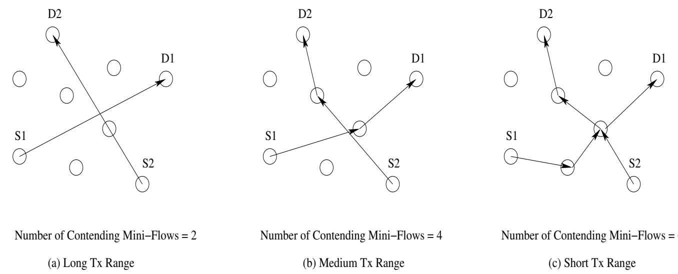


Fig. 3. Illustration of Number of Contending Mini-Flows vs. Transmission Range

is evident from Figure 2(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-count ratio is around 4:1. Also, most interestingly, the number of contending flows (Figure 2(c)) increases as the transmission range decreases. Because shorter transmission range increase the number of hops for each end-to-end flow, the number of contending mini-flows increases. 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 (see Figure 3 for illustration).

For example, node ID 70 experiences the maximum contention (35 mini-flows) when a transmission range of $300m$ is used. On the other hand, when a transmission range of $1500m$ is used, the maximum contention is among 20 mini-flows. The corresponding utilization curve for IEEE 802.11 shows that when flows are transmitting at 60Kbps, a change in the number of flows from 20 (at maximum transmission range) to 35 (at minimum 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.

C. Impact of Load

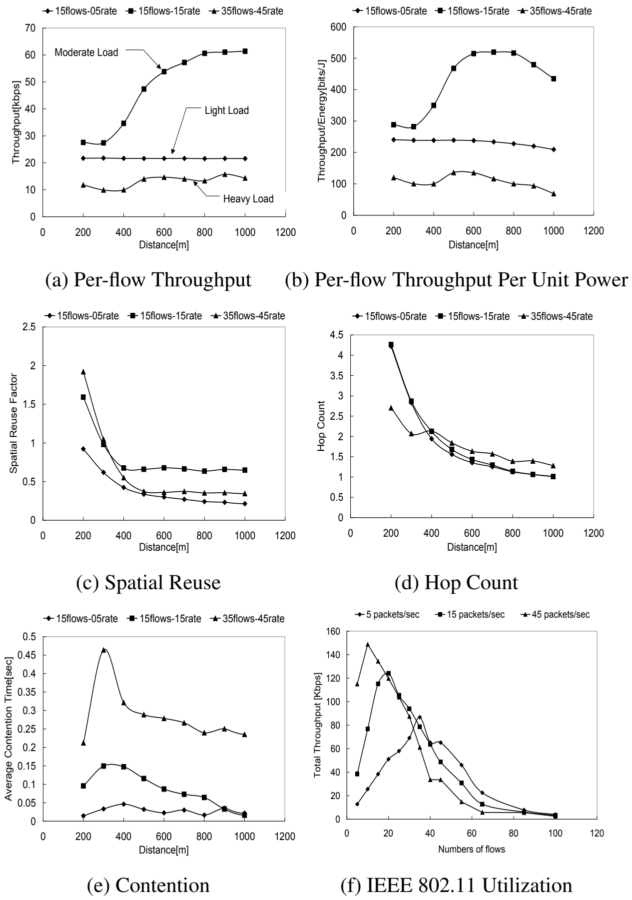
Figure 4 shows the results observed when the number of nodes and network size are fixed at 100 and 1000m X 1000m respectively. To observe the impact of various traffic loads, we use three different loads: 5 flows, 15 flows, and 45 flows with each flow having a data rate of 60Kbps. From Figure 4(a) it can be observed that (i) for the lightly loaded scenario, the maximum per-flow throughput is achieved at a low transmission range of 300m; (ii) for the moderately loaded scenario, the maximum per-flow throughput is achieved at a transmission range of approximately 800m; and (iii) for the heavily loaded scenario, the utilization is poor and the maximum per-flow throughput is achieved approximately at 1000m (the throughput curve is relatively flat for this scenario and close to maximum throughput is achieved at 500m).

For given environments, this illustrates the following fact:

The optimal transmission range to maximize throughput is variable and is a function of the load in the network.

Note that the contention in terms of number of flows increases even in the case of the lightly loaded scenario, but as seen in Figure 4(f), the utilization of IEEE 802.11 is scalable with increasing number of flows when the number of flows is fewer. For the moderately loaded scenario, because the utilization of IEEE 802.11 is already near the peak on the utilization curve, any increase in the contention degrades the throughput. In the heavily loaded scenario, the utilization is already on the far right side of the utilization curve and hence any increase in contention only decreases the throughput marginally.

It is important to note that a transmission range of 1000m will have a transmission power that is approximately 4-16 times more than the

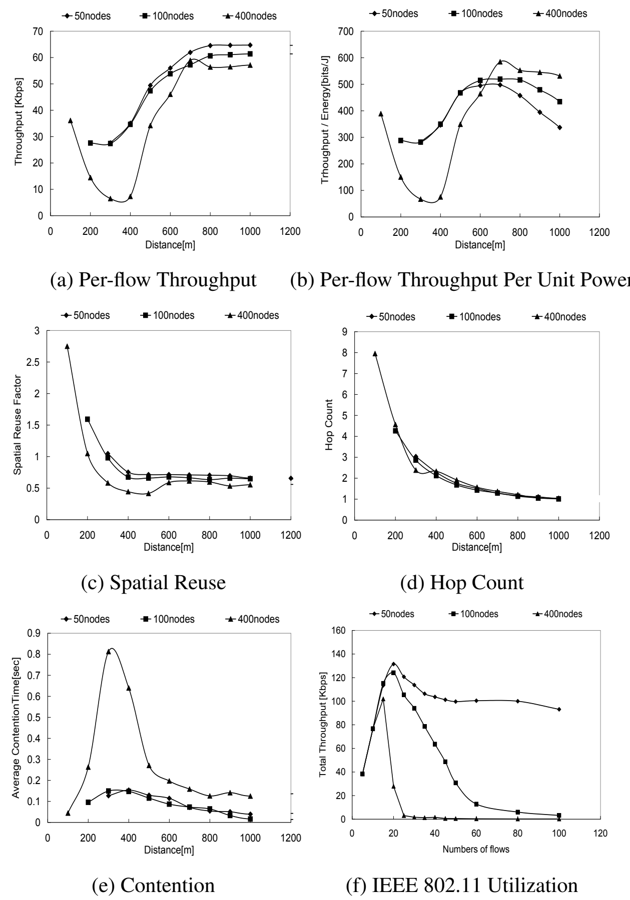


(a) Per-flow Throughput (b) Per-flow Throughput Per Unit Power

(c) Spatial Reuse (d) Hop Count

(e) Contention (f) IEEE 802.11 Utilization

Fig. 4. Various Load, Fixed Number of Nodes, Fixed Network Size



(a) Per-flow Throughput (b) Per-flow Throughput Per Unit Power

(c) Spatial Reuse (d) Hop Count

(e) Contention (f) IEEE 802.11 Utilization

Fig. 5. Fixed Load, Various Number of Nodes, and Fixed Network Size

transmission power required for a transmission range of 500m. Hence, we also present the throughput per unit energy results for the scenarios. The peaks of this result are at 300m, 800m, and 500m for the lightly loaded, moderately loaded, and heavily loaded scenarios respectively.

An interesting observation is that although the transmission power ratios between two transmission ranges, say 500m and 1000m, is around 1:16, the net energy consumption when operating at the two transmission ranges are not in the same ratios. The reason is quite intuitive since a station transmitting at a rate of 60Kbps is actively transmitting only 5% of the time and is either receiving or idle for the remaining time. Hence, the increase in transmission power affects the energy consumption only for that 5% of the time. Thus, the bottleneck when increasing the transmission range to larger values will be the transmission power restrictions on the device rather than the energy consumption itself.

We now try to explain the reasons behind the throughput and throughput per energy consumption results observed using Figures 4(c), 4(d), and 4(e). The spatial re-use factor stays below 2 for all scenarios while the hop-count 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 hump at around 300-400m indicating lower utilization and thus explaining the lower throughput at those transmission ranges.

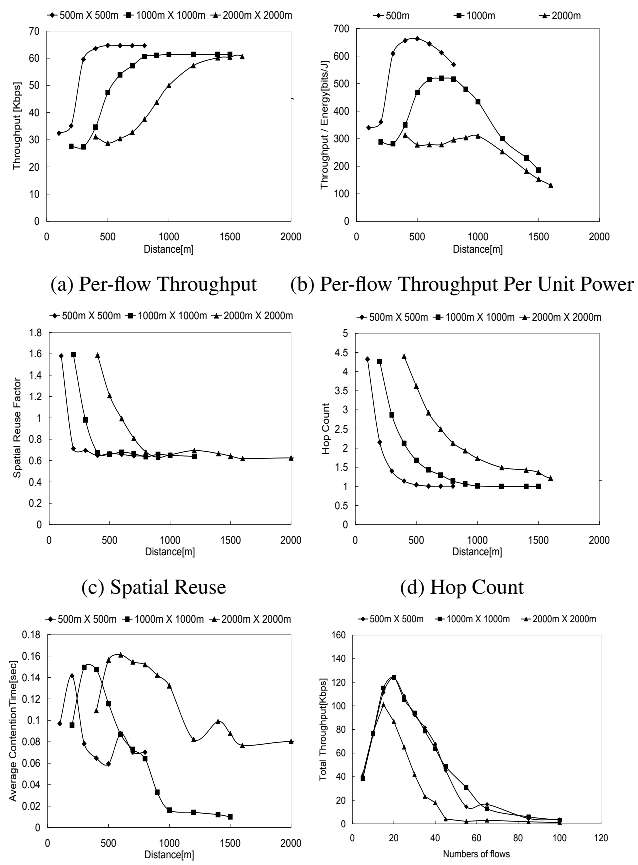
D. Impact of Number of Nodes

Figure 5 shows the results for the various number of nodes. The network size is 1000m X 1000m and load is moderate. 50, 100, and 400 nodes respectively are used to demonstrate the impact of load. Observing the throughput result, the key observation is that the maximum throughput still occurs at a transmission range much higher than the minimal transmission range. However, the optimal transmission range for the 400 nodes scenario has reduced to 700m when compared to 800m for the other two scenarios. This seems to be an indication that if the number of nodes is further increased, the optimal transmission range might shift towards lower values.

An impact of increasing the number of nodes is to decrease the minimal transmission range necessary to keep the network connected. Hence, for the 400 nodes scenario, the minimal transmission range has decreased to a distance of 100m. Another interesting observation is the throughput achieved at the minimal transmission range. As the distance decreases (with increase in number of nodes) the throughput achieved at the minimal transmission range increases. This again substantiates our earlier conjecture that the optimal transmission range might converge to the minimal transmission range for large number of stations. In section V, we provide some intuitive analysis on how many stations would be required for this convergence to occur, and therein argue the atypical nature of such scenarios.

E. Impact of Network Size

Figure 6 shows the results for variable network sizes. The number of stations is 100 and load is moderate. The network sizes used to study the impact of network size are 500m X 500m, 1000m X 1000m, and 2000m X 2000m respectively. As expected, the minimal transmission range decreases with decrease in network size. However, there is marginal difference in the throughput across the different scenarios at the minimal transmission range. This is in contrast to the observation



(a) Per-flow Throughput (b) Per-flow Throughput Per Unit Power

(c) Spatial Reuse (d) Hop Count

(e) Contention (f) IEEE 802.11 Utilization

Fig. 6. Fixed Load, Fixed Number of Nodes, and Various Network Size

in the previous scenario where the throughput increased at the minimal transmission range as the distance decreased. An explanation for this can be given based on the hop-count curves. When the network size is changed and the number of nodes is kept constant, the topology at the minimal transmission range does not change, consequently not affecting both the hop-count and spatial re-use On the other hand, in the results for the impact of number of nodes, the hop-count and the spatial re-use increases with more number of nodes as the diameter of the graph increases.

An important effect of the impact of network size is illustrated by the throughput and throughput per energy curves for the network size of 2000m. Although like in the cases of the other network sizes, the throughput peaks at a range much higher than the minimal transmission range, the throughput per energy curve peaks at the minimal transmission range. This is because of the significant increase in energy consumption as the network size increases. This leads us to the conclusion that beyond a certain network size the energy consumption will become the bottleneck preventing the achievement of the maximum possible throughput.

V. Analysis of Constant Transmission Power

To understand the previous observations on the throughput of constant power control scheme, we present the analytical throughput model of constant power control scheme. Because this paper assumes an ad-hoc network which uses the IEEE 802.11 distributed coordination function (DCF) mode, we restrict the throughput model to the 802.11 DCF mode. In related literatures, there are several throughput models [12], [13] which present throughput model as a function of the size of a packet and the size of backoff window. We, however, derive the throughput model as a function of transmission range to explain the phenomenon: "Under typical ad-hoc environments, throughput increases as transmission range increases." And we explain the reason of phenomenon comparing two influential factors under the typical ad-hoc environments.

A. Analytical Models of Influential Factors

1) Spatial Re-use: Because the transmission power changes the radius of transmission area of a node, it also has a relationship with the spatial re-use factor. (1) defines the spatial re-use factor σ as a function of the area of network and the transmission range r(For IEEE 802.11, β can be determined to be ≈ 20). Previous observations in section IV show that every spatial re-use factor σi is smaller than hop count h.

$$\sigma = \frac{D^2}{\beta * r^2} \tag{1}$$

2) Hop Count: We compute the expected Euclidean distance(ED) between two nodes(a source and a destination of a flow) randomly chosen within a square grid of size D as follows:

$$ED = 4*D*\int_0^1 \int_0^1 \sqrt{x^2+y^2}(1-x)(1-y)dxdy = 0.52*D \tag{2}$$

As the number of nodes in the grid approaches *infinity*, the hop count between the source and the destination will approach:

$$h = \frac{ED}{r} = \frac{0.52 * D}{r} \tag{3}$$

B. Throughput As a Function of Transmission Range

Before describing the relationship between the optimal transmission range and throughput, we define a simple expression for throughput Γ given by

$$\Gamma = \Gamma_{mc} * \sigma = \frac{\lambda * T_s * \sigma}{T_c + T_s} = \frac{\lambda * \sigma}{\eta + 1} \tag{4}$$

where λ is the flow rate of each mini-channel, σ is the spatial re-use factor, T_s is the successful transmission time of a packet, and T_c is the average contention time, which excludes the successful transmission time T_s. (4) assumes that the whole network is partitioned into several mini-channels. Any transmission within the mini-channel does not interfere with transmissions on another mini-channel. Therefore, the total throughput can be defined as the sum of throughputs for each mini-channel. The total throughput will be the function of a flow rate, a number of mini-channel, and a η which is the ratio contention time to transmission time $\eta = \frac{T_c}{T_s}$.

If we assume a proportional relationship (as the ρ increases, the contention time T_c increases. Therefore η increases.), we can approximate the ratio η as

$$\eta = k * \rho^{\phi} \tag{5}$$

where ρ is the mini-flow density or the number of one-hop transmissions contending with each other per unit area. ρ can be defined as

$$\rho = \frac{N_f * h}{D^2} \tag{6}$$

where N_f is the number of flows.

If (3), (5) and (6) are used in (4), throughput Γ can be obtained as

$$\Gamma = \frac{\lambda * \sigma}{k * (\frac{0.52 * N_f}{r * D})^{\phi} + 1} \quad (7)$$

Based on (5), it can be expected that the throughput should decrease as the transmission range r increases.

However, investigating (1) more carefully, it is evident that spatial re-use factor σ will be close to 1 in case of typical environments (100nodes, 1000mX1000m area). Also, observing the results shown in Figure 4(f), at moderate loads, the rate λ has minimal impact on the throughput. Hence, assuming $\phi \approx 1$, when the transmission range is of the same order as D, throughput Γ can be written as

$$\Gamma \propto \frac{r * D * \lambda}{N_f} \quad (8)$$

Therefore, for a given number of flows N_f , a given network grid size D, and a typical number of nodes, Throughput Γ increases as transmission range r increases.

C. Spatial Re-use vs. Hop Count

As proved in the previous section, the throughput increases as the transmission range increases in a typical ad-hoc network. In this section, we identify the scale of the network required to observe performance improvements at the minimal transmission range. First, we derive simple relationships for the spatial re-use factor and hop count as a function of the number of nodes in the network. Assuming even distribution of stations in the network, an approximation for the minimal transmission range required for network connectivity can be obtained as:

$$r = \frac{2 * D}{\sqrt{\pi * n}} \quad (9)$$

Furthermore, the spatial re-use factor can be approximated as:

$$\Gamma = m_1 * \frac{D^2}{\beta * r^2} = m_1 * \frac{\pi * n}{4 * \beta} \quad (10)$$

where m_1 is a constant. The hop count, as introduced before can be obtained as:

$$h = m_2 * \frac{0.52 * D}{r} \approx m_2 * \frac{\sqrt{\pi * n}}{4} \quad (11)$$

Based on results observed through simulations, empirically setting m_1 and m_2 to 0.25 and 1.0 respectively, Figure 7 shows the progression of the spatial re-use and the hop count for increasing n. It can be observed that the effects of spatial re-use begins to surpass that of hop count only when the number of nodes is significantly more than 2,000. Although it is possible to deploy more than 2,000 nodes, it is not general to practical application. Therefore, under general environments, because the effect of spatial re-use cannot be larger than that of hop count, minimum transmission cannot achieve maximum throughput.

Consequently, the idea, which minimum transmission range achieves maximum throughput, should be changed into another idea, which transmission range should be changed adaptively to achieve maximum throughput.

VI. CONCLUSIONS

Transmission power control in multi-hop wireless networks is a relatively under-studied problem. Most existing approaches to power control implicitly assume that using the minimal transmission power required to keep the network connected is the optimal operating point.

In this paper, we show that in contrast, the optimal transmission range is dependent on the network environment defined by (i) traffic load, (ii) mobile node density, and (iii) network grid size.

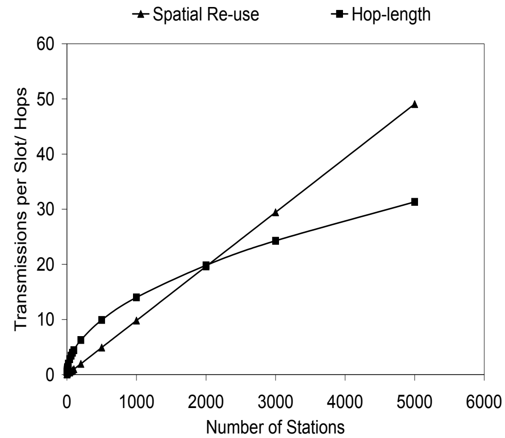


Fig. 7. Projection of Spatial re-use and Hop-length

We substantiate our arguments with comprehensive simulations results in a variety of scenarios. We, moreover, present the analytical throughput model as a function of transmission range to support our argument: "Minimum transmission power cannot always provides maximum throughput of ad-hoc network."

In the future, we plan to design the adaptive power control scheme which changes the transmission power based on network environments.

REFERENCES

[1] "Zero Configuration Networking," in *IETF zeroconf Working Group*.

[2] R. Ramanathan and R. R-Hain, "Topology Control of Multihop Wireless Networks using Transmit Power Adjustment," in *Proceedings of IEEE INFOCOM*, Mar. 2000.

[3] Roger Wattenhofer, Li Li, Paramvir Bahl, and Yi-Min Wang, "Distributed Topology Control for Ad-hoc Networks," in *Proceedings of IEEE INFOCOM*, Apr. 2001.

[4] V. Kawadia, S. Narayanaswamy, R. S. Sreenivas R. Rozovsky, and P.R. Kumar, "Protocols for Media Access Control and Power Control in Wireless Networks," in *Proceedings of the 40th IEEE Conference on Decision and Control*, Orlando, FL, USA, Dec. 2001, pp. 1935–1940.

[5] Elizabeth M. Royer and Charles E. Perkins, "Transmission Range Effects on AODV Multicast Communication," in *To appear in ACM Mobile Networks and Applications special issue on Multipoint Communication in Wireless Mobile Networks*.

[6] "Mobile Ad-hoc Networking," in *IETF MANET Working Group*.

[7] J. Monks, V. Bharghavan, and W. Hu, "Transmission Power Control for Multiple Access Wireless Packet Networks," in *Proceedings of IEEE LCN*, Nov. 2000.

[8] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, "Span: An Energy Efficient Coordination Algorithm for Topology Maintenanc in Ad Hoc Wireless Networks," in *Proceedings of ACM MOBICOM*.

[9] K. Fall and K. Vardhan, "ns notes and documentation," http://www-mash.cs.berkeley.edu/ns/, 1999.

[10] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva, "A Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols," in *Proc. IEEE MOBICOM*, Dallas, TX, Oct. 1998.

[11] J. Broch, D. B. Johnson, and D. A. Maltz, "The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks," Internet Draft draft-ietf-manet-dsr-03.txt, Oct. 1999.

[12] Giuseppe Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE JSAC*, vol. 18, no. 3, March 2000.

[13] F. Cali, M. Conti, and E. Gregori, "IEEE 802.11 Wireless LAN: Capacity Analysis and Protocol Enhancement," in *Proceedings of IEEE INFOCOM*, 1998, pp. 142–149.