Power Control for Distributed MAC Protocols in Wireless Ad Hoc Networks

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Abstract—In wireless networks that use centralized transmission scheduling, reducing the transmission power normally leads to higher network transport throughput. In this paper, we investigate power control and spatial utilization in a different scenario, where the network adopts distributed MAC-layer coordination mechanisms. We first consider the widely adopted RTS/CTS-based MAC protocols. We show that an optimal power control protocol should use higher transmission power than the "just-enough" power in order to improve spatial utilization. The optimal protocol has a minimal transmission floor area of $\Theta(d_{ij}d_{max})$, where d_{max} is the maximal transmission range, and d_{ij} is the link length. This surprisingly implies that if a long link is broken into several short links, then the sum of the transmission floors reserved by the short links is still comparable to the floor reserved by the long link. Thus, using short links does not necessarily lead to higher transport throughput. Another consequence of this is that, with the optimal RTS/CTS based MAC, rate control can at best provide a factor of two improvement in transport throughput. We then extend our results to other distributed MAC protocols that use physical carrier sensing or busy tone as the control signal. Our simulation results show that the optimal power control scheme outperforms other popular MAC-layer power control protocols. We also validate our analysis regarding the impact of routing choices via extensive simulations.

Index Terms—Wireless ad hoc networks, power control, MAC protocols.

1 Introduction

In wireless networks, the channel is a shared resource for all users. Nearby transmitter-receiver pairs can interfere with each other, and therefore, the number of links that can be activated simultaneously is constrained. From this point of view, we can treat both the space and time utilized for transmissions as a shared resource [1]. Therefore, efficient utilization of this limited (space-time) resource is key to improving the performance of ad hoc networks.

Transmission power control is a technique for increasing the efficiency of space-time utilization in wireless networks. Loosely speaking, reducing the transmission power causes less interference to nearby receivers. Therefore, more links can be activated simultaneously, improving the overall throughput of the network. Gupta and Kumar show that the network capacity can be achieved through centralized assignment of transmission power and network traffic [2]. However, typical wireless ad hoc networks do not have centralized coordinators. It is difficult for a node in ad hoc networks to predict the future transmissions of its neighbors. Thus, instead of centralized assignment, distributed MAC protocols are widely adopted in wireless networks for contention resolution. In this paper, we investigate the space-time utilization in distributed MAC systems and show that some of the conclusions drawn from the centralized system do not hold any more.

There is a common belief that using *just-enough* power to reach the receiver will both reduce the transmission energy consumption and increase the network throughput. Most distributed power control schemes [3], [4], [5] adopt a *linear power assignment* scheme, as defined in [6]. Such schemes use transmission power of Cd_{ij}^{α} for a link (i, j) with length d_{ij}, where C is a constant, and α is the path-loss exponent. Linear power assignment achieves a *just-enough* received power level for the receiver to successfully decode the message; thus, the sender introduces minimal interference to other nearby nodes. Such power assignment is efficient when the transmission power and schedule are centrally assigned. However, linear power assignment overlooks some side effects when distributed MAC protocols are used.

In distributed MAC protocols, it is necessary to disseminate *collision avoidance information* (CAI) to resolve collisions. Most distributed MAC protocols use control messages to carry the CAI such as request to send/clear to send (RTS/CTS) exchange [7], physical carrier sensing [8], [9] or busy tone [3]. To avoid collision, transmitters/receivers need to send out control messages to block future transmissions that may interfere with them. Linear power assignment achieves the same received power level at the receiving end for different link lengths. Thus, all receivers have the same tolerance for future interference no matter how close the transmitter-receiver pair is. This leads to a uniform transmission range for control messages; i.e., we need to clear the same size of region around the receiver, irrespective of the link length. As we will show later, this requires the control messages to cover neighboring nodes

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within a long distance, which is of the order of the maximal transmission range, even for a short link. In other words, a short link with linear power assignment may need to block senders in a large region for a collision-free transmission, which actually wastes the limited space-time resource.

How can the space-time utilization be improved in such distributed MAC schemes? We observe that there is a basic trade-off between transmission power (which determines how much interference the link has introduced to the channel) and interference tolerance (which determines how many future transmissions are blocked by the link) when selecting the transmission power for a particular link. When the transmitter increases transmission power, the signal strength at the receiver is higher. As a result, the receiver only needs to inform nodes within a smaller area to keep silent during its reception. On the other hand, if the transmitter reduces its power, the receiver is more susceptible to interference and will have to block transmissions in a larger area. On the other hand, the transmitter will introduce less interference to other nearby links in this case. This implies that there is an optimal power that minimizes the space-time usage of a link, considering both the interference introduced by the transmitter and the number of future transmissions blocked by the receiver.

We first use a simple model, which is the RTS/CTS protocol with a fixed transmission rate, to investigate this basic trade-off in distributed MAC systems. The transmission floor of a link in such protocols is the union of the RTS/CTS region; i.e., nodes either in the RTS range or the CTS range of an existing transmission cannot send any packet. To meet the Signal-to-Interference-plus-Noise Ratio (SINR) requirements for a certain data rate, the receiver needs to properly set the range of CTS according to the transmission power of the data/RTS packet used by the transmitter. In order to increase the aggregated throughput, we minimize the transmission floor used in each transmission subject to the SINR constraint of capture threshold β. We show that for a link (i, j) with a link length of d_{ij}, the minimal transmission floor is $\Theta(\beta^{1/\alpha} d_{ij} d_{max})$, where d_{max} is the maximal transmission range, and α is the path loss exponent. The maximal transmission range normally is a constant for a given network to make the network become connected. This implies that the transmission floor is proportional to link distance and not the *square* of the distance. Consequently, we show that routing mechanisms that favor short hops over long hops give at most a constant factor improvement in network throughput. This indicates that power control can reside at the MAC layer, and selecting shorter hops in the routing layer has little effect in improving the network throughput in RTS/CTS-based systems.

We then extend our results to other distributed MAC solutions, including rate-adaptive MAC, physical carrier sensing, and sending a busy tone in a separate control channel. We show that with the optimal RTS/CTS-based MAC scheme, changing the transmission rate with respect to the link distance can at most increase the throughput by a factor of 2. Also, our conclusion drawn from the RTS/CTS scheme holds in both physical carrier sensing and busy-tone approaches, which implies that the trade-off between transmission power and interference tolerance is deeply rooted in distributed MAC systems. Finally, we conduct extensive simulations to prove that the choice of hop length has little effect on performance and also show that our MAC protocol outperforms linear power assignment schemes and the 802.11 protocol.

The main results and contributions in this paper are listed as follows:

- We first investigate the trade-offs in power control for networks using distributed MAC protocols. We show that reducing the transmission power does not necessarily lead to less "interference" to other links.
- Based on the analysis, we propose a new power assignment scheme for RTS/CTS-based MAC protocols, which can minimize the transmission floor of a given link. And, the area of the transmission floor is proportional to $d_{ij} d_{max} \beta^{\frac{1}{\alpha}}$, where d_{ij} and d_{max} are the link length and the maximum transmission range, respectively.
- Based on our analysis on space-time utilization, we show that routing mechanisms that favor short hops over long hops can give at most a constant factor improvement in network performance. This indicates that power control should reside at the MAC layer and not at the routing layer.
- We extend our results drawn from the RTS/CTS system to other distributed MAC systems. We show that with the optimal RTS/CTS-based MAC scheme, changing the transmission rate with respect to the link distance can at most increase the throughput by a factor of 2.

The rest of this paper is organized as follows: Section 2 summarizes the related works in this area. Section 3 investigates power control on control messages and proposes a new way of controlling the power of RTS/CTS. Section 4 shows that routing layer is less important in power control when using our protocol. Section 5 extends the analysis to more generalized cases and discusses the trade-offs in a general sense. Section 6 gives the simulation results on different distributed power control schemes. Finally, Section 7 concludes this paper.

2 Related Work

There are two major objectives for power control at the MAC layer: one is to improve the space-time utilization [3], [4], and the other is to save the energy used in transmission [10].

For energy-conserving MAC protocols, Jung et al. show that transmissions with lower power are more vulnerable to interference [10]. Nodes outside the maximal transmission range of RTS/CTS may still be able to interfere with the receiver when the transmission power is reduced. The solution suggested in [10] is to periodically increase the power level to the maximum and use physical carrier sensing to alert potential interfering nodes. However, the major objective of this protocol is energy saving, and short links consume the same transmission floor as long links in this protocol, resulting in poor space-time utilization.

Physical carrier sensing has been used as a method of protecting long-distance transmissions in 802.11 [8], [9]. However, the physical carrier sensing area is centered at the *sender*, which may only overlap partially with the interfering area around the *receiver* [11]. Thus, physical carrier sensing generally reserves a larger transmission floor than the CTS area, which we will further discuss in Section 5.

In order to improve space-time utilization, many MAC protocols use a separate channel to send control messages [3], [4]. A busy-tone-based approach is proposed in [3]. In this protocol, transmitters use just-enough power to guarantee a constant interference tolerance margin at the receiver. To avoid collision, the receiver will send a busy tone in a separate channel to inform nearby nodes. A single-channel solution is proposed in [5] to save the separate channel for a busy tone. In this protocol, neighboring links will negotiate their transmission powers within an access time window after the CTS of the first transmitter-receiver pair. Then, they will begin data transmission simultaneously with the first pair. This approach is similar to using a time-division channel for control messages. All these approaches use linear power assignment or its variants, in which the reserved interference margin is independent of link distance. In this paper, we use power assignment schemes other than linear power assignment to improve the network space-time utilization.

Recently, Moscibroda et al. show that both the linear power assignment and the uniform power assignment in 802.11 are suboptimal for link scheduling [6], [12]. Using a power level between these two schemes, they construct an efficient scheduling algorithm for network connectivity. However, the main focus of [6] is network connectivity and not space-time utilization. In this paper, we do not study the space-time utilization for centralized scheduling. Instead, we consider distributed MAC protocols and show that using a transmission power that lies between linear and uniform assignment improves the spatial reuse significantly.

Power control can also reside at the routing layer as network topology control [13], [14] or power-controlled routing schemes [1], [15]. Several power control schemes such as COMPOW [1] and CLUSTERPOW [15] are proposed for the link layer. The power-controlled routing schemes try to assign a globally optimal transmission power for each transmission. However, routing schemes still depend on the MAC layer to resolve collision. A power assignment may be optimal from the view of routing, but it may be impossible to schedule it in a distributed manner. Joint routing and scheduling algorithms may solve the problem [16]. However, such protocols are usually centralized, and the optimal solution is known to be NP-complete.

3 Power Control for RTS/CTS-Based Systems

3.1 System Model and Assumptions

In this section, we study the space-time utilization in a simple model of RTS/CTS-based systems with fixed transmission rates. This model will be extended to more general cases in later sections.

We consider RTS/CTS-based MAC protocols, where each transmission pair reserves a transmission floor by exchanging RTS/CTS messages [7]. The control messages are sent in the same channel as data packets. A node that is within the transmission floor (either in the RTS or the CTS range) of another transmission pair cannot transmit or receive. We assume that a node has no knowledge of future transmissions in the vicinity before they occur. For simplicity, we assume that RTS messages and data packets are transmitted at the same power level. We also do not consider physical carrier sensing in this section. We will relax these two assumptions in Section 5.

We assume that the transmission signal power decays with distance d as $d^{-\alpha}$, where α is a constant with range of 2-4. Suppose that node i is sending data to node j with transmission power $P_t^{(i)}$. If the distance between nodes i and j is d_{ij}, then the received power $P_r^{(i)}(j)$ at node j is

$$P_r^{(i)}(j) = \frac{P_t^{(i)} G_{ij}}{d_{ij}^{\alpha}}, \quad (1)$$

where G_{ij} is the antenna gain.[1] In the following sections, we assume that all nodes are using the same omnidirectional antenna, so we treat G_{ij} as a constant G.

We assume that the message can be successfully decoded when the SINR at the receiver is larger than a predefined capture threshold β:

$$\frac{P_r^{(i)}(j)}{\sum_{k \neq i} P_r^{(k)}(j) + P_n(j)} \geq \beta, \quad (2)$$

where $P_r^{(k)}(j)$ is the interference caused by the simultaneous transmission of node k, and $P_n(j)$ is the noise level at node j. In the following discussions, we assume that all nodes experience the same noise level of P_n.

We use the metric of *Transport Capacity* introduced in [2] to evaluate the performance of a network. For a particular network, we define its transport throughput as the sum of products of the rate and link length over all simultaneously active links, which is measured in bit-meters per second. The transport capacity considers both the end-to-end throughput and the summed end-to-end distance between the source-destination pairs. Therefore, a network that can transmit at 2 megabits per second (Mbps) over an end-to-end distance of 10 m has a higher capacity than a network that can transmit at the same rate over 1 m.

3.2 Power Control of RTS/CTS: Constant Rate

We first consider power control in RTS/CTS-based systems with a fixed transmission rate. Note that the nodes in the RTS range may be unnecessarily blocked, so this protocol is not as efficient as the other MAC mechanisms that we will discuss later. However, this approach catches some basic properties of interference in wireless networks. Loosely speaking, the RTS range can serve as a measurement of how much interference the sender introduces to its neighbors when transmitting the RTS/data packet. The CTS range will be the measurement of "interference" introduced by the receiver that blocks future transmissions around it. Our protocol minimizes the overall "interference" so that the spatial utilization can be increased. This point will become clearer in our later discussions on other distributed MAC protocols.

1. Here, G_{ij} accounts for the antenna gain of both the transmitter and the receiver.

The simple RTS/CTS framework that we study here resembles the IEEE 802.11 protocol. In the IEEE 802.11 MAC protocol, the RTS/CTS exchange reserves a fixed area for transmission, irrespective of the distance between transmitter and receiver. This results in poor spatial utilization [5]. Furthermore, the fixed CTS range cannot prevent collisions for long links [17]. The received power decreases to the receiving threshold when the link distance is close to the maximal transmission range. Therefore, nodes outside the CTS area can still interfere with long links [17]. To address these problems, we introduce a scheme that adjusts the power of RTS/CTS to maximize spatial utilization while preventing collisions.

In our power control scheme, each link strives to minimize its transmission floor in order to maximize the spatial utilization of the network. The reason behind this is explained as follows: As we have assumed, a node cannot predict the future transmissions around it. Also, when the transmitter-receiver pair initializes the transmission, none of them should have received *any* RTS/CTS messages sent by ongoing transmissions. This implies that the transmitter and the receiver also have no knowledge about ongoing transmissions. Since nodes do not have information of ongoing and future transmissions, it is impossible for nearby links to cooperatively adjust the transmission power so that their transmission floors can "fit" with each other to increase the spatial utilization. Therefore, in our distributed system, each link can only independently minimize its own transmission floor, which is the union of the RTS and the CTS regions, to improve the spatial utilization of the whole network. Theorem 1 gives the lower bound of the transmission floor required by a link with a length of d_{ij}.

Theorem 1. *For a transmitter-receiver pair (i, j) separated by the distance of d_{ij}, the minimum transmission floor reserved by the RTS/CTS-based system is $\Theta(\beta^{1/\alpha} d_{max} d_{ij})$, where d_{max} is the maximum transmission range used in the network.*

Proof. Consider a transmitter-receiver pair (i, j). Using (1) and (2), the maximal interference that the receiver j can tolerate (power margin at node j) is

$$P_{margin}(j) = \frac{P_t^{(i)} G}{d_{ij}^{\alpha} \beta} - P_n. \tag{3}$$

If a node k is transmitting at the maximal power P_{max} and has a distance of d_{kj} to the receiver and if we have

$$P_r^{(k)}(j) = \frac{P_{max} G}{d_{kj}^{\alpha}} \geq \frac{P_t^{(i)} G}{d_{ij}^{\alpha} \beta} > P_{margin}(j), \tag{4}$$

then node k will interfere with the reception of node j. From (4), we have

$$d_{kj} \leq \left(\frac{P_{max} d_{ij}^{\alpha} \beta}{P_t^{(i)}} \right)^{\frac{1}{\alpha}}. \tag{5}$$

Define $d_{int}(j) = \left(\frac{P_{max} d_{ij}^{\alpha} \beta}{P_t^{(i)}} \right)^{\frac{1}{\alpha}}$, which is the distance threshold within which a node transmitting at P_{max} can interfere with node j's reception from node i.

In wireless ad hoc networks, it is difficult for a node to predict the future transmissions and the transmission power that its neighbors will use, especially when nodes are mobile. In heavily loaded systems, node j needs to inform all potential interferers to stay silent. Then, the transmission range of CTS should be at least $d_{int}(j)$. Note that we only consider the interference of one neighbor to get the lower bound on the CTS range of $d_{int}(j)$. When more than one neighbor can interfere the transmission, the CTS range should be even larger than $d_{int}(j)$. Thus, $d_{int}(j)$ gives a *lower bound* for the reserved transmission floor. To ensure that all nodes within $d_{int}(j)$ can decode the CTS message, the received power of the CTS at a distance $d_{int}(j)$ must satisfy

$$\frac{P_t^{(j)} G}{d_{int}^{\alpha}(j)} \geq P_{recv} \tag{6}$$

to make the neighbors hear the CTS message, where P_{recv} is the receiver sensitivity. Consequently, the CTS transmission power should be

$$P_t^{(j)} \geq \frac{P_{recv} P_{max} d_{ij}^{\alpha} \beta}{P_t^{(i)} G}. \tag{7}$$

Note that the required CTS power can be larger than P_{max} when $\beta > 1$ and d_{ij} is close to d_{max}. To comply with the maximal transmission power, the possible link length of d_{ij} should be smaller than d_{max} in this case. Otherwise, the CTS message will not be able to inform all possible interfering neighbors.

From (7), we see that the transmission power $P_t^{(j)}$ of the CTS is inversely proportional to the transmission power $P_t^{(i)}$ of data and RTS. So, there is a trade-off between the transmission power of RTS and CTS. When we reduce the power of the data packet, we need to increase the power of CTS accordingly, since the receiver is more vulnerable to interference.

The maximal transmission range is given by

$$d_{max} = \left(\frac{G P_{max}}{P_{recv}} \right)^{\frac{1}{\alpha}}. \tag{8}$$

Combining (7) and (8), we get

$$P_t^{(j)} P_t^{(i)} \geq \left(\frac{d_{ij}}{d_{max}} \right)^{\alpha} P_{max}^2 \beta. \tag{9}$$

The transmission range of CTS and RTS, defined as $d_c = (P_t^{(j)} G / P_{recv})^{1/\alpha}$ and $d_r = (P_t^{(i)} G / P_{recv})^{1/\alpha}$, will satisfy

$$\begin{aligned} d_c d_r &= \left(P_t^{(j)} P_t^{(i)} \right)^{1/\alpha} \left(\frac{G^2}{P_{recv}^2} \right)^{1/\alpha} \\ &\geq \frac{d_{ij}}{d_{max}} \left(\frac{P_{max}^2 G^2 \beta}{P_{recv}^2} \right)^{1/\alpha} \\ &= \beta^{1/\alpha} d_{max} d_{ij}. \end{aligned} \tag{10}$$

Recall our system assumptions. We try to minimize the union of the area consumed by the RTS and CTS messages. Let the area of the transmission floor be $A_{ij}(d_c, d_r)$. This area must be larger than the RTS or the CTS region. Thus, we have[2]

$$A_{ij}(d_c, d_r) \geq \max\{\pi d_c^2, \pi d_r^2\}. \quad (11)$$

The selection of d_c and d_r is subject to the following constraints:

$$\begin{aligned} d_c d_r &\geq \beta^{1/\alpha} d_{max} d_{ij}, \\ d_c &\geq d_{ij}, \\ d_r &\geq d_{ij}. \end{aligned} \quad (12)$$

When $\sqrt{\beta^{1/\alpha} d_{max} d_{ij}} > d_{ij}$, it is easy to see that $\max\{d_c, d_r\} \geq \sqrt{\beta^{1/\alpha} d_{max} d_{ij}}$, and we get

$$\min_{d_c, d_r}\{A_{ij}(d_c, d_r)\} \geq \pi \beta^{1/\alpha} d_{max} d_{ij}. \quad (13)$$

If $\sqrt{\beta^{1/\alpha} d_{max} d_{ij}} < d_{ij}$, we have $d_{ij} > \beta^{1/\alpha} d_{max}$. This only happens when $\beta < 1$ and d_{ij} is large. In this case, we have $d_c \geq d_{ij}$ and $d_r \geq d_{ij}$. Since d_{ij} is bigger than $\beta^{1/\alpha} d_{max}$, the reserved floor is also larger than $\pi \beta^{1/\alpha} d_{max} d_{ij}$.

It is easy to see that $A_{ij}(d_c, d_r)$ is actually minimized when we have $d_c^* = d_r^* = \sqrt{\beta^{1/\alpha} d_{max} d_{ij}}$. This hints an optimal way of setting the transmission power, given the link distance. Under this optimal power control scheme, we can further upper bound the area of reserved transmission floor as

$$\begin{aligned} \min_{d_c, d_r}\{A_{ij}(d_c, d_r)\} &\leq \pi d_c^{*2} + \pi d_r^{*2} \\ &= 2\pi \beta^{1/\alpha} d_{max} d_{ij}. \end{aligned} \quad (14)$$

Together with the lower bound in (13), we see that

$$\pi \beta^{1/\alpha} d_{max} d_{ij} \leq \min_{d_c, d_r}\{A_{ij}(d_c, d_r)\} \leq 2\pi \beta^{1/\alpha} d_{max} d_{ij}. \quad (15)$$

Thus, the area of reserved floor is $\Theta(\beta^{1/\alpha} d_{max} d_{ij})$ when using the optimal power control scheme.

Note that this scheme assumes that there is only one interfering node. When there are multiple interfering senders, we can simply increase d_{int} by a constant factor of $(\frac{8}{\alpha - 2})^{1/\alpha}$ when $\alpha > 2$ (see the Appendix). In that case, the reserved floor still remains as $\Theta(\beta^{1/\alpha} d_{max} d_{ij})$. □

2. The actual expression for $A_{ij}(d_c, d_r)$ is

$$\begin{aligned} A_{ij}(d_c, d_r) = \pi d_c^2 + \pi d_r^2 - d_c^2 \cos^{-1}\left(\frac{d_{ij}^2 + d_c^2 - d_r^2}{2 d_{ij} d_c}\right) - d_r^2 \cos^{-1}\left(\frac{d_{ij}^2 + d_r^2 - d_c^2}{2 d_{ij} d_r}\right) \\ + \frac{1}{2}\sqrt{(-d_{ij} + d_c + d_r)(d_{ij} - d_c + d_r)(d_{ij} + d_c - d_r)(d_{ij} + d_c + d_r)}, \end{aligned}$$

when $|d_c - d_r| < d_{ij}$. It can be shown that the minimal value of this function is achieved at $d_c^* = d_r^* = \sqrt{\beta^{1/\alpha} d_{max} d_{ij}}$. To avoid cumbersome mathematical manipulations, we only study the lower bound.

3.3 Comparison with Linear Power Assignment

Linear power assignment chooses a transmission power to guarantee a fixed receiving power level of ρP_{recv}, where ρ is a constant [3]. In such a scheme, we have

$$P_t^{(i)} = \frac{\rho P_{recv} d_{ij}^{\alpha}}{G}, \quad (16)$$

$$d_{int}(j) = \left(\frac{G P_{max} \beta}{\rho P_{recv}}\right)^{\frac{1}{\alpha}}. \quad (17)$$

Using the expression of d_{max} in (8), the transmission range of CTS is $d_{int}(j) = (\beta/\rho)^{\frac{1}{\alpha}} d_{max}$, which is a constant comparable to d_{max}. Therefore, even when nodes i and j are very close to each other, node j still needs to send the CTS to clear a transmission floor with an area proportional to πd_{max}^2. We observe that when the CTS is sent in the same channel as data packets, linear power assignment suffers from the same problem as 802.11, i.e., the area taken by the CTS is proportional to d_{max}^2, irrespective of the link distance. When the CTS is sent in the same channel as the data, it will also interfere with the data transmission. Therefore, most linear power assignment schemes use a separate control channel for the CTS/busy tone so that the interference generated by the CTS/busy tone can be minimized. However, this does not totally resolve the problem, which we will discuss in Section 5.

4 Discussions on RTS/CTS-Based Systems

4.1 Routing-Layer Choices

In Section 3, we see that the optimal transmission range of the RTS and CTS is $\Theta(\sqrt{d_{ij}})$ and the optimal transmission floor area A_{ij} will be $\Theta(d_{ij})$. This leads to a surprising conclusion that the routing layer plays a minor role in power control. Suppose that we have a source node S that wishes to send messages to a destination node D. In a dense network, we can either route the messages by a large number of short links or by a small number of long links. At first glance, the first choice seems superior, since short links use much smaller space than long links. However, there is actually not much difference in spatial utility, since the total transmission floor will be $\Theta(d_{ST})$ for both cases when the optimal transmission power control is used.

In the following sections, we will investigate the spatial utility improvement of routing layer choices more carefully. We assume that the optimal power control scheme is used. We also assume that some node will use the maximal transmission power, which gives a transmission range of d_{max}, to achieve network connectivity or for broadcasting. To prevent interference from such nodes, every link must reserve a transmission floor area lower bounded by Theorem 1.

4.1.1 Uniform Link Length

We first study routing protocols that choose a uniform link length of d for most data transmissions, while the maximal power may be used occasionally for broadcasting or other operations.

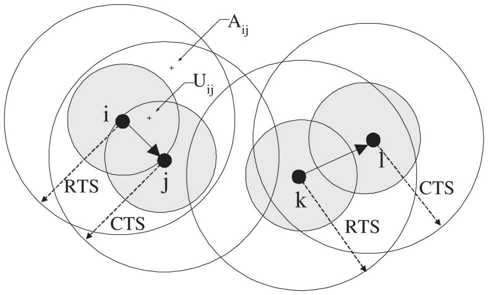


Fig. 1. Overlapping of transmission floors when a uniform link distance is used.

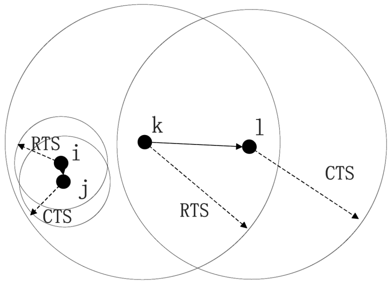


Fig. 2. The transmission floor of short links is totally included in the floor of long link.

Theorem 2. *For a network deployed in a field with area A, if all links are using the same transmission range of d and the transmission rate of R, the maximal total transport throughput of the network is $T = \Theta(\frac{AR}{\beta^{1/\alpha} d_{max}})$.*

Proof. Consider two concurrent transmitting links (i, j) and (k, l). The optimal RTS/CTS range will be $d_r^* = d_c^* = \sqrt{\beta^{1/\alpha} d_{max} d}$. Therefore, any two nodes in different links must be separated by more than d_c^*; otherwise, they will be in the RTS/CTS range of other links. In this case, the union of disks of radius $0.5 d_c^*$ centered at i and j (denoted by U_{ij}) cannot overlap with the union of disks of the same radius centered at k and l (denoted by U_{kl}; see Fig. 1). Since the area of U_{ij} is larger than $\frac{\pi}{4} {d_c^*}^2$, the maximal number of simultaneous transmissions in the network with an area of A is upper bounded by

$$N \leq \frac{A}{Area\ of\ U_{ij}} \leq \frac{4A}{\pi \beta^{1/\alpha} d_{max} d}, \tag{18}$$

and the maximal transport throughput is upper bounded by

$$T \leq \frac{A}{Area\ of\ U_{ij}} \times Rd \leq \frac{4AR}{\pi \beta^{1/\alpha} d_{max}}, \tag{19}$$

where R is the transmission rate, and each link contributes transport throughput of Rd. Note that this bound holds for any value of d smaller than the longest transmission range permitted by the power limit of P_{max}.[3]

We use a packing approach to get the lower bound for the transport throughput [18]. In a packing problem, one looks at how well an area can be filled with nonoverlapping randomly deployed shapes such that the remaining area is minimized. Packing density is the fraction of covered area after it has been packed to the limit with nonoverlapping shapes. The packing density for uniform-sized disks in a plane is nearly 0.56, which means that 56 percent of the total area can be occupied by randomly packed disks [19]. Consider packing disks with uniform radius $d + 2 \times \frac{d_c^*}{2}$. Each of these disks contains one U_{ij}; thus, each of them can contain a transmission without overlapping with others. Since the packing density of such disks is 0.56, we can pack at least $\frac{0.56A}{\pi \times (d + d_c^*)^2}$ transmissions simultaneously, given that the network is dense enough. The transport throughput is

$$\begin{aligned} T &\geq 0.56 \times \frac{ARd}{\pi \times \left(d + d_c^*\right)^2} \\ &= 0.56 \frac{AR}{\pi(d + 2\sqrt{\beta^{1/\alpha} d_{max} d} + \beta^{1/\alpha} d_{max})} \\ &= 0.56 \frac{AR}{\pi \beta^{1/\alpha} d_{max} \left(\frac{d}{\beta^{1/\alpha} d_{max}} + 2\sqrt{\frac{d}{\beta^{1/\alpha} d_{max}}} + 1 \right)} \\ &\geq 0.56 \frac{AR}{\pi \beta^{1/\alpha} d_{max} (\beta^{-1/\alpha} + 2\beta^{-1/2\alpha} + 1)}. \end{aligned} \tag{20}$$

By defining a constant $\nu = \frac{0.56}{\beta^{-1/\alpha} + 2\beta^{-1/2\alpha} + 1}$, we can bound throughput T between two constants:

$$\frac{\nu AR}{\pi \beta^{1/\alpha} d_{max}} \leq T \leq \frac{4AR}{\pi \beta^{1/\alpha} d_{max}}, \tag{21}$$

irrespective of the link length d. □

By Theorem 2, for a fixed maximal transmission range, no matter how small the link length d chosen by the routing layer is, the transport throughput can at most be improved by a constant factor.

4.1.2 Heterogeneous Link Length

When heterogeneous link lengths are used, the nonoverlapping argument used above no longer holds. A short link, which can tolerate more interference, may get its transmission floor fully included in a long link's transmission floor when it transmits first. Considering Fig. 2, assume that the short link (i, j) starts the transmission before link (k, l). Since (i, j) transmits its RTS/CTS at a small power, nodes k and l cannot hear the RTS/CTS of link (i, j). Thus, it is possible that links (i, j) and (k, l) transmit simultaneously. Due to the high tolerance of the short link, the long link will not interfere with it. In this case, the transmission floor of the short link is totally included in the long link, so there is no exclusively reserved floor for link (i, j). Therefore, the simple packing arguments used earlier do not hold anymore, and it is hard to get tight bounds on the transport throughput.

However, the upper bound cannot be increased by a factor of more than $O(\log n)$ in random networks. Consider a random uniformly distributed network of n nodes. To make the network connected, d_{max} must be $O\left(\sqrt{\frac{\log n + \kappa(n)}{n}}\right)$,

3. Note that the longest data range is not exactly d_{max} when the optimal RTS/CTS has a range of d_{max}, $d_{ij} = \frac{d_{max}}{\beta^{1/\alpha}}$.

where $\kappa(n) \to \infty$ as n increases [20]. Substituting this into (21), we get a transport throughput of $O(\sqrt{n/\log n})$. The per-node throughput is $O(1/\sqrt{n \log n})$. Since the per-node throughput of an arbitrary network with n nodes is upper bounded by $O(1/\sqrt{n})$ [2], the throughput benefits from considering heterogeneous link length is bounded by $O(\sqrt{\log n})$. We conjecture that for random networks, such overlaps in the transmission floor will at most increase the throughput by a constant factor. We validate this conjecture by simulation results in Section 6. Moreover, even if the benefit of combining links of different lengths can improve the throughput by more than a constant factor, finding the optimal link distribution that can maximize the spatial reuse is still an open problem.

4.2 Power Control in Routing Layer

The RTS/CTS mechanism is the most widely used collision-resolving method. However, the network throughput of such protocols is mainly decided by a global parameter, i.e., the maximal transmission range d_{max}, as shown in Theorem 2. In most ad hoc networks, the maximal transmission distance is a predefined network parameter to guarantee network connection. So, the routing-layer choices cannot greatly affect the network throughput.

Due to randomness in the network topology, certain regions in the network may have a higher node density. To utilize the high node density, some routing-layer protocols propose to choose shorter links in clusters with a higher density [15]. However, the short link needs to clear a certain area to avoid collision by nodes using the maximal transmission power for intercluster communication or broadcasting. From Theorem 2, the network throughput improvement of such protocols is upper bounded by a constant factor when RTS/CTS-based MAC protocols are used.

The above discussions hint that power control should be done at the MAC layer, especially when the major objective of power control is throughput improvement. However, when the major objective of power control is to save energy, the routing layer can still choose shorter links to reduce the transmission energy.

4.3 Energy Consumption

Aside from increasing the network throughput, the other main objective of power control is to reduce the energy used in transmission. Since the transmission power decreases as d^{α} with the distance d in linear power assignment, when a long link is broken into several short links, the total energy used in transmission can be saved [13].

From (9), the optimal transmission power for link with length d_{ij} is

$$P_t^{(i)} = \left(\frac{d_{ij}}{d_{max}}\right)^{\alpha/2} P_{max} \beta^{1/2} = C_p d_{ij}^{\alpha/2}, \qquad (22)$$

where $C_p = \beta^{1/2} d_{max}^{-\alpha/2} P_{max}$ is a constant. In our scheme, the transmission power decreases with the link length in a much slower fashion. When $\alpha = 2$, the power used in transmission will be $C_p d_{ij}$. Thus, when we break long links into short links, the sum of energy used in transmission over the short links is the same as that used over the long link. In other words, one does not obtain much savings in energy by transmitting over shorter hops when $\alpha = 2$. Shorter links will result in smaller total power consumption only for $\alpha > 2$. This shows that our optimal transmission range for spatial utilization is not optimal for energy saving. If the main objective is energy saving, we need to sacrifice some throughput for energy. We can send data by linear power assignment while increasing the power of CTS. The total energy consumption can be reduced, since the CTS packet is normally much shorter than data packets.

4.4 Link Asymmetry

Link asymmetry is an important issue in transmission power control schemes [21], [22]. Power control schemes reduce the transmission power of short links. This may cause fairness problems in RTS/CTS-based systems. Consider the short link (i, j) in Fig. 2. The nearby long link (k, l) cannot hear the RTS/CTS of link (i, j), so it will always assume that the channel is idle, even when (i, j) is transmitting. On the other hand, when the link (k, l) is transmitting, node (i, j) will be blocked by the RTS/CTS of (k, l). This may lead to the starvation of link (i, j), as shown in [21] and [22].

Our optimal power control scheme can mitigate the starvation problem by properly selecting the transmission power. The transmission power for node i in our scheme is large enough so that node k cannot interfere link (i, j) once the transmission of node i has started. When node k transmits first, node i can learn the transmission finish time of node k's packet from the RTS/CTS packet of link (k, l). At the end of node k's transmission, both nodes i and k will use a contention-based protocol such as the IEEE 802.11 DCF to compete for the channel. In this case, node i can have a nearly similar probability as in node k to win the contention, and the link (i, j) will not be starved. However, the short link still cannot have a fair access on the channel in this situation. The long link (k, l) can always access the medium, while the short link (i, j) needs to contend with link (k, l) before it can access the channel. This phenomenon will be further studied in our simulations.

4.5 Remarks on Optimal Power Selection

We propose the optimal power control scheme to investigate the bounds for transmission floors in the ideal case. Although implementation issues are out of the scope of this paper, our power control mechanism can be easily implemented in the MAC layer when the path loss $Loss_{ij} = P_r^{(i)}(j)/P_t^{(i)} = G/d_{ij}^{\alpha}$ between the transmitter and the receiver can be measured. The optimal transmission power can then be set as $P_t^* = \frac{\sqrt{\beta P_{max} P_{recv}}}{\sqrt{Loss_{ij}}}$. Note that the numerator only contains fixed hardware parameters for a given transmission rate. Thus, we only need to measure the path loss for the given link to calculate the transmission power.

5 Spatial Utilization in Other Distributed MACs

The simplified RTS/CTS system in Section 3 provides some insights to the trade-offs in distributed MAC systems. However, are these observations dependent on the model that we used? To answer this question, we study several more sophisticated distributed MAC protocols in this section:

1. **Rate-adaptive MAC.** The node can adapt its transmission rate according to the interference that it experienced. The link can tolerate more interference when the transmission rate is reduced. Thus, more nearby links can be activated simultaneously, and the links can be "packed" more densely. In this section, we will study the trade-offs between transmission rate reduction and the increase in active link density.
2. **Physical carrier sensing.** Physical carrier sensing [8], [9] is widely used in distributed MAC systems. In these systems, the carrier signal of the data packet will act as an implicit control signal to block potentially interfering neighbors. In this section, we compare the physical carrier sensing approach with an RTS/CTS system and show the spatial utility of this approach.
3. **Busy tone.** We also consider more efficient protocols that use busy tone sent in separated channels as control messages [3]. RTS/CTS-based schemes unnecessarily block exposed nodes that are only close to the transmitter so that they only hear the RTS message but not the CTS message. This makes RTS/CTS schemes less efficient compared to the busy-tone approach. The busy-tone scheme only blocks interferers around the receiver and allows nodes around the transmitter to send. Moreover, nodes that hear the busy tone can also dynamically determine whether its transmission will interfere with the ongoing transmissions. When it can use a low transmission power without interfering with the ongoing transmissions, it is also allowed to transmit.

5.1 Rate-Adaptive MAC

If we increase the transmission rate, the transmission time for a given packet can be reduced. Therefore, more data can be transmitted within a given time duration. The price paid for higher transmission rates is that such transmissions are more vulnerable to interferences, and it requires a larger transmission floor.

In this section, we study the trade-offs between the transmission rate and the required transmission floor size. The transmission rate R depends on the received SINR. Suppose that each transmitter-receiver pair can choose its own capture threshold β and transmission rate $R(\beta)$. This adds one more dimension to the transmission space-time minimization problem. Consider the space-time taken by a packet with a length of L bits. We need to minimize the transmission floor multiplied by the time that the link occupies the floor, which is $\frac{A_{ij}(d_c,d_r)L}{R(\beta)}$. From (15), the minimal space-time floor is within $[\frac{\pi\beta^{1/\alpha}Ld_{max}d_{ij}}{R(\beta)}, \frac{2\pi\beta^{1/\alpha}Ld_{max}d_{ij}}{R(\beta)}]$ for a given value of β.

Suppose that we fix the capture threshold to β^*, which minimizes the function $f(\beta) = \frac{\beta^{1/\alpha}}{R(\beta)}$. By (15), any selection of (β, d_c, d_r) cannot use a space-time floor smaller than $\frac{\pi(\beta^*)^{1/\alpha}Ld_{max}d_{ij}}{R(\beta^*)}$, since β^* gives a minimum value of $\frac{\beta^{1/\alpha}}{R(\beta)}$. When we fix β to β^*, we can choose d_c^* and d_r^* as in Section 3. As shown by (15), this scheme uses space-time of at most $\frac{2\pi(\beta^*)^{1/\alpha}Ld_{max}d_{ij}}{R(\beta^*)}$. Therefore, even if we change the β according to the current interference conditions, the space-time used by the transmission cannot be two times smaller than using a fixed β^*. Thus, using a fixed rate is order optimal within a factor of 2.

For example, in an Additive White Gaussian Noise (AWGN) channel, the channel capacity is given by

$$R(\beta) \leq W \log_2 (1 + \beta), \tag{23}$$

where W is the bandwidth. So, we can find the β^* that minimizes the function $f(\beta) = \frac{\beta^{1/\alpha}}{W \log_2 (1+\beta)}$ and use this fixed β^* for all links. By setting the derivative $f'(\beta)$ to 0, β^* must satisfy

$$\alpha\beta = (1 + \beta)ln(1 + \beta). \tag{24}$$

Equation (24) has a positive solution $\beta^* > 0$ when $\alpha > 1$. For example, we can get $\beta^* = 3.92$ when $\alpha = 2$.

When the optimal rate $R(\beta^*)$ is high, links with long distances close to d_{max} may not be able to use the optimal rate due to the limitation on transmission power. In this case, we can use reduced rate for long links or remove long links to ensure that all links are using transmission power smaller than P_{max}.

5.2 Physical Carrier Sensing

Physical carrier sensing normally has a larger effective range than CTS, because the carrier sensing threshold P_{phy} is much lower than P_{recv}. For a fixed carrier sensing threshold of P_{phy}, the carrier sensing range can be expressed as

$$d_{phy} = d_d \times (P_{recv}/P_{phy})^{1/\alpha}, \tag{25}$$

when the data transmission range is $d_d = (P_t^{(i)} G/P_{recv})^{1/\alpha}$, where $P_t^{(i)}$ is the data packet transmission power. Since the physical carrier sensing region is centered at the transmitter instead of the receiver, to block all possible interfering nodes, we need to have

$$d_{phy} \geq d_{ij} + d_{int}(j). \tag{26}$$

Similar to (10), we also have the relationship of $d_d d_{int}(j) \geq \beta^{1/\alpha} d_{max} d_{ij}$. Substituting (25) into (26), we get

$$\begin{aligned} d_d \left(\frac{P_{recv}}{P_{phy}}\right)^{1/\alpha} &\geq d_{ij} + d_{int}(j) \\ &\geq d_{ij} + \frac{\beta^{1/\alpha} d_{max} d_{ij}}{d_d} \\ &> \frac{\beta^{1/\alpha} d_{max} d_{ij}}{d_d}. \end{aligned} \tag{27}$$

Thus, we have $d_d > \sqrt{(P_{phy}/P_{recv})^{1/\alpha}\beta^{1/\alpha}d_{max}d_{ij}}$. Applying (25), we have

$$d_{phy} \geq \sqrt{(P_{recv}/P_{phy})^{1/\alpha}\beta^{1/\alpha}d_{max}d_{ij}}. \quad (28)$$

As $(P_{recv}/P_{phy})^{1/\alpha}$ is constant for a given protocol, physical carrier sensing also takes a transmission floor of $\Theta(\beta^{1/\alpha}d_{max}d_{ij})$. Moreover, since P_{recv}/P_{phy} normally is bigger than 1, we see that physical carrier sensing takes a larger transmission floor than the RTS/CTS approach.

For physical carrier sensing that considers a rate-SINR trade-off [8], we can use similar arguments as in rate-adaptive MAC to show that adapting rates at most improves the throughput by a constant factor.

5.3 Busy-Tone Approach

5.3.1 System Model

The busy-tone approach described in [3] uses a separate channel for the receiver to send a "busy" signal while it is receiving a packet. The busy tone will notify nodes around the receiver so that they will not interfere with it. Consider a transmitter/receiver pair (i, j). Similar to the analysis in Theorem 1, the receiver j needs to notify nodes within $d_{int}(j)$ when the transmitter i uses a transmission power of $P_t^{(i)}$. The receiver uses a busy tone that is sent with a power of [3]:

$$P_t^{(j)} = \frac{d_{int}^{\alpha}(j)P_{phy}}{G}, \quad (29)$$

where P_{phy} is the carrier sensing threshold. So, the busy tone sent by the receiver j can be sensed at a distance of $d_{int}(j)$. Define the transmission range of the busy tone as $d_b = (P_t^{(j)}G/P_{phy})^{1/\alpha} = d_{int}(j)$. A potentially interfering node k within d_b will sense the busy tone and refrain from using the maximal transmission power to send a packet during the reception of node j. The busy-tone approach still allows the node k to use a smaller power, which will not interfere with node j, for it to transmit, even it is within a distance of d_b to node j. Suppose that the transmitter k receives the busy tone from node j with a power of $P_r^{(j)}(k)$. Then, the transmission power budget that node k can use is defined as [3]

$$P_{budget}(k) = \min\left\{\frac{P_{max}P_{phy}}{P_r^{(j)}(k)}, P_{max}\right\}. \quad (30)$$

Thus, the power budget for a node k closer to the receiver j will be smaller. By (1), it is easy to see that the interference of node k at node j will be smaller than $P_{margin}(j)$ if node k keeps its power to be smaller than $P_{budget}(k)$. The busy-tone approach can achieve very high spatial utilizations, since it only blocks transmissions where the transmission power is high enough to interfere with ongoing transmissions. Also, the control message (busy tone) is transmitted in a separate channel that can use high power without interfering with data packets.

5.3.2 Linear Power Assignment in Busy Tone

Many busy-tone schemes use linear power assignment, in which the transmission range of a data packet d_d decreases as $O(d_{ij})$. However, we show in Section 3.3 that the transmission range of the busy tone is $O(d_{max})$ for linear power assignment. Thus, both long links and short links will use nearly the same transmission power to send the busy tone.

The fact that long links and short links have nearly the same busy-tone range makes the system unfair to long links. As a short link can use small transmission powers, it can be activated, even when the transmitter/receiver hears the busy tone of other links. Once activated, the short link takes nearly the same resources in the busy-tone channel as long links. They will block all long links in their busy-tone range and only allow short links to transmit within that range. As short links have a much higher probability of being activated than long links in the same neighborhood, long links will rarely get a chance to be activated in a heavily loaded network.

Furthermore, the transport throughput for a single link is proportional to the link distance. Short links have smaller transport throughput than long links. But, they take nearly the same resources as long links in the busy-tone channel in linear power assignment schemes. This implies that linear power assignment is not efficient in spatial reuse for busy-tone schemes.

5.3.3 Optimal Power Assignment Rule

We make the same assumptions as in Section 3 when deriving the optimal power assignment rule for busy-tone schemes. We assume that nodes cannot obtain enough information to cooperatively optimize the transmission floor used by different links. Note that nodes actually can have partial knowledge about the ongoing transmissions by listening to the busy tone and data channel. However, it is hard for nodes to calculate the location of the current transmitter/receiver in order to cooperate with them. So, we assume that links independently optimize their transmission power to improve the spatial utility. The problem of cooperative power assignment will be considered in future work.

In order to improve the spatial utility, a link needs to minimize the "interference" that it introduces to the channel. The "interference" of a link can be broken into two parts. First, the transmission power emitted by the transmitter interferes with receivers in other links. Second, the busy tone transmitted by the receiver blocks the transmitters of other links. We use the total number of possible future links blocked by a link (i, j), denoted as I_{ij}, to quantitatively study the interference of the link.

Consider a link (k, l) that is close to an active link (i, j). When d_{kj} is larger than d_b, node k will not sense the busy tone, and it can use P_{max} to send its packet. When $d_{kj} = \gamma d_b$, with $0 < \gamma < 1$, by (1) and (30),we have the power budget of node k as

$$P_{budget}(k) = \gamma^{\alpha} P_{max}. \quad (31)$$

If the transmission power budget $P_{budget}(k)$ for node k is too small for it to reach its receiver l, the link (k, l) will be blocked.

Node j needs to estimate the expected number of *transmissions* blocked by the busy tone that it sent without knowing the future traffic patterns. As nodes in wireless ad hoc networks can move, node j can only assume that traffic is uniformly distributed around it, with an intensity of λ. Under this assumption, the expected number of transmissions initiated on a region with area A will be λA per unit of time. For a given transmission attempt on link (k, l), whether it can be activated depends both on the link distance d_{kl} and the power budget of $P_{budget}(k)$. If the link distance is too long and the power budget is not enough, the link will be blocked. As node j has no information on the link distance distribution around it, it is rational for node j to assume that the link distance distribution is stationary and independent of the position of node k. Therefore, given a power budget of $P_{budget}(k)$, the probability that the link will be blocked can be calculated as $1 - F_b(P_{budget}(k)) = 1 - \mathbb{P}\{P_t^{(k)} < P_{budget}(k)\}$, where $F_b(P)$ is the Cumulative Distribution Function of the transmission power used by node k. As we will show later, the exact expression of $F_b(P)$ is not important for the calculation. We only require that $F_b(P)$ is independent of the location of node k.

The expected number of transmission blocked by the busy tone of node j during the packet transmission time of t_p can be expressed as[4]

$$\begin{aligned} I_{ij}^b(d_b) &= t_p \int_0^1 (1 - F_b(\gamma^\alpha P_{max})) \times \lambda 2\pi(\gamma d_b) d_b \, d\gamma \\ &= t_p d_b^2 \int_0^1 2\pi\lambda\gamma(1 - F_b(\gamma^\alpha P_{max}))\, d\gamma \\ &= C_b t_p d_c^2, \end{aligned} \tag{32}$$

where $C_b = \int_0^1 2\pi\lambda\gamma(1 - F_b(\gamma^\alpha P_{max}))d\gamma$ is a constant for a given node j.

Similarly, the transmitter i in link (i, j) can also block future transmissions by interfering with neighboring receivers. Consider the interference of node i when the data transmission range of node i is d_d. By (1), a receiver l, which has distance of ωd_d to i, will experience an interference of $P_r^{(i)}(l) = \omega^{-\alpha} P_{recv}$. We can also assume that with a probability of $F_d(P_r^{(i)}(l)) = \mathbb{P}\{P_{margin}^{(l)} < P_r^{(i)}(l)\}$, the receiving of l will be blocked. So, the number of transmissions blocked by the transmission of node i can be expressed as

$$\begin{aligned} I_{ij}^d(d_d) &= t_p \int_0^\infty F_d(\omega^{-\alpha} P_{recv}) \times \lambda 2\pi(\omega d_d) d_d \, d\omega \\ &= t_p d_d^2 \int_0^\infty 2\pi\lambda\omega F_d(\omega^{-\alpha} P_{recv})\, d\omega \\ &= C_d t_p d_d^2, \end{aligned} \tag{33}$$

where $C_d = \int_0^\infty 2\pi\lambda\omega F_d(\omega^{-\alpha} P_{recv})\, d\omega$ is a constant.

Therefore, the total number of transmissions blocked by link (i, j) will be a function of the data transmission range of d_d and the busy-tone range of d_b in a similar way as in Section 3. Note that if a transmission is blocked by both the busy tone and the interference of link (i, j), it will appear in both $I_{ij}^b(d_b)$ and $I_{ij}^d(d_d)$. So, the expected number of $I_{ij}(d_b, d_d)$ is smaller than the sum of $I_{ij}^b(d_b)$ and $I_{ij}^d(d_d)$. However, we can bound it in a similar way as in Section 3:

$$\max\left\{I_{ij}^b(d_b), I_{ij}^d(d_d)\right\} \le I_{ij}(d_b, d_d) \le I_{ij}^b(d_b) + I_{ij}^d(d_d). \tag{34}$$

Equivalently, we have

$$\max\{C_b t_p d_b^2, C_d t_p d_d^2\} \le I_{ij}(d_b, d_d) \le C_b t_p d_b^2 + C_d t_p d_d^2. \tag{35}$$

We also have the relationship of $d_d d_b \ge \beta^{1/\alpha} d_{max} d_{ij}$ as in (10). In the busy-tone case, it is difficult to calculate the intersection of $I_{ij}^b(d_b)$ and $I_{ij}^d(d_d)$. However, we still can apply the same bounds as in (15) by substituting d_b and d_d with $d_b' = \sqrt{C_b} d_b$ and $d_d' = \sqrt{C_d} d_d$. The bounds will be changed to

$$\begin{aligned} \min_{d_b, d_d}\{I_{ij}(d_b, d_d)\} &\ge \sqrt{C_b C_d} t_p \beta^{1/\alpha} d_{max} d_{ij}, \\ \min_{d_b, d_d}\{I_{ij}(d_b, d_d)\} &\le 2\sqrt{C_b C_d} t_p \beta^{1/\alpha} d_{max} d_{ij}. \end{aligned} \tag{36}$$

So, the number of transmission blocked by the optimal choice of d_d and d_b is $\Theta(t_p \beta^{1/\alpha} d_{max} d_{ij})$. Also, the choice of $d_b = d_d = \sqrt{\sqrt{C_b C_d} \beta^{1/\alpha} d_{max} d_{ij}}$ will be order optimal in this case. This shows that the trade-offs in power control for busy-tone systems are similar to the RTS/CTS-based systems.

The above derivations show that our results can be extended to many MAC protocols other than RTS/CTS-based systems. In recent years, directional antenna [23], multiple-channel systems [24], and MIMO systems [25], [26] have become important ways of increasing the network throughput. The trade-off between transmission power and interference tolerance described in this paper also exists in such systems, and results in this paper may also be useful. The performance of power control in these systems will be interesting future research topics.

4. Here, we only consider the busy tone blocking the transmitter k. In certain protocols, the link will also be blocked if the receiver l cannot reply to the transmitter. We can include such cases by simply increasing the λ in (32).

TABLE 1
Parameters Used in Simulation

Data packet size	1KB
Data link speed	2Mbps
Carrier frequency	2.472GHz
Capture threshold (β)	6 dB
Receiver sensitivity (P_{recv})	-64 dBm
Maximal transmission power (P_{max})	24.5 dBm

6 Experimental Results

6.1 Simulation Setup

We evaluate the performance of different power control schemes by using the *ns2* network simulator (version 2.28). The parameters used in the simulation are summarized in Table 1. These settings give a maximal transmission range $d_{max} \approx 250$ m. We turn off the physical carrier sensing in the MAC layer and use only CTS messages to avoid collisions. We use on-off messaging in the simulation, i.e., nodes hearing a RTS or CTS will defer their transmission. All our simulations run on single-channel systems, where the data and control messages are sent through the same channel.

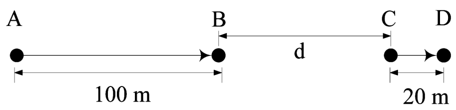


Fig. 3. The string topology used in simulation.

In this section, we first compare the performance of our MAC protocol with 802.11 and linear power assignment protocols. We show that our MAC protocol outperforms the other MAC protocols in most scenarios. We then investigate the effect of choosing long hops versus short hops at the routing layer.

6.2 Comparison to Other Power Control Schemes

Our simulation compares power control schemes as follows:

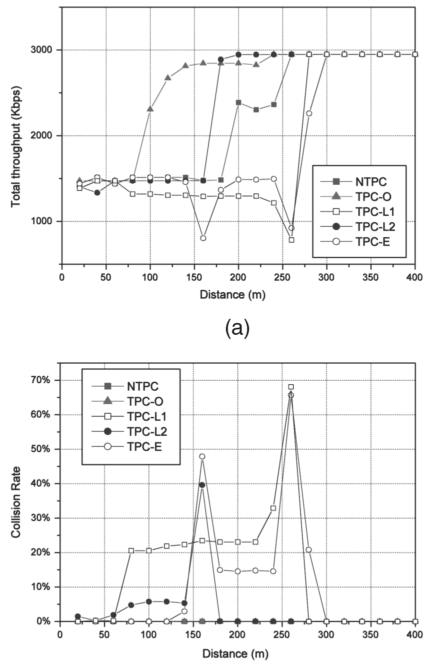
- ***NTPC*** (no power control). This protocol sends RTS, CTS, and data in the maximal power, which is just the 802.11 MAC protocol with the physical carrier sensing turned off.
- ***TPC-O*** (optimal power control). In this scheme, RTS, CTS, and data are sent at the optimal power as derived in Section 3.
- ***TPC-L1*** (linear power assignment 1). This scheme uses linear power assignment for RTS and data, i.e., RTS and data are sent at a power, which ensures that the received power is just 3 dB above P_{recv}. In this scheme, the CTS is sent using maximal power to prevent collisions.
- ***TPC-L2*** (linear power assignment 2). The only difference between TPC-L1 and TPC-L2 is that the CTS power in TPC-L2 is the same as the data/RTS power. Thus, this scheme uses minimal transmission floor for short links. However, it takes the risk of a high collision rate.
- ***TPC-E*** (power control for energy saving). This scheme sends RTS/CTS at maximal power but uses linear power assignment for data transmission. Such schemes are usually used for saving transmission energy, which is the BASIC protocol in [10].

Note that for TPC-O, TPC-L1, and TPC-L2, the required power for RTS/CTS may exceed P_{max} when the transmission range is close to d_{max}. In this case, we only use P_{max} to send the control message.

6.2.1 String Topology

We first use a string topology to show the basic behavior of each power control scheme. The topology contains four nodes, as shown in Fig. 3. There are two single-hop transmission pairs: $A \rightarrow B$ and $C \rightarrow D$. Each transmission uses a constant bit rate flow of 8 Mbps, which is enough to saturate a single link. The distance between the source and the destination is 100 m and 20 m, respectively. In the experiment, we fix the link distances and move the second pair (nodes C and D together) to the left. At each test point, we fix the position of nodes for a time period and record the throughput and collision rate. The results are shown in Fig. 4.

When the distance d between nodes B and C is smaller than 100 m, all nodes can hear each other. Therefore, the two pairs share the transmission space-time, and all schemes give a total throughput of nearly 1.5 Mbps. As nodes C and D move away, the two pairs become decoupled gradually. The TPC-O scheme decouples first at the point that the distance between nodes B and C is larger than 100 m, where node B is out of the RTS/CTS range of nodes C and D. Hence, nodes A and B can communicate at maximal rate, while nodes C and D can transmit when they are not blocked by node B's CTS.



(a)

(b)

Fig. 4. Performance comparison in string topology. (a) Aggregated throughput. (b) Data collision rate.

Although TPC-L2 also has a smaller RTS/CTS range, the reduced data transmission power for the pair C and D makes the link between C and D vulnerable. The CTS of node B can easily collide with link $C \rightarrow D$. This can be seen in the collision rate graph (see Fig. 4b). The collision rate of TPC-L2 rises when d is close to 150 m, where node B's CTS cannot be heard by node C. Yet, it will interfere with node D's reception. This phenomenon can also be seen in TPC-E. The only difference is that TPC-E has two peak collision rates: one at 160 m and another one at 260 m. The first peak is due to that node A cannot hear the RTS/CTS of the second pair, and its RTS message can collide with their transmission. The second peak is because node B cannot hear the RTS/CTS of the second pair, and its CTS message collides with their transmission.

TPC-L1 uses full power for CTS but smaller power to send data and RTS. In this scheme, when the distance between nodes B and C is larger than 60 m, the two pairs cannot hear each other's RTS. This causes the increase in collision rate to be beyond 60 m. Unlike TPC-L2 and TPC-E, the collision rate of TPC-L1 does not go up at 150 m. This is because the maximal power CTS of node D can block node B, while in TPC-L2, the power-reduced CTS cannot. Also, the RTS in TPC-L1 uses a smaller power and thus will not collide node C's transmission as in TPC-E.

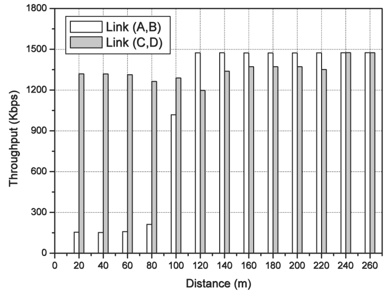


Fig. 5. Link asymmetry in TPC-O.

The comparison shows that TPC-O and TPC-L2 can increase the spatial utilization by decoupling two transmissions when they are close. But, only NTPC and TPC-O can provide perfect collision avoidance. The TPC-L1, TPC-L2, and TPC-E schemes can cause severe collisions, which may reduce the throughput.

Fig. 5 shows the throughput of links (A, B) and (C, D) under TPC-O. When d is smaller than 100 m, node B can hear the RTS of node C, while node A cannot. Therefore, node B can only respond to the RTS message sent by node A when node C is not sending. As node A has no information on the transmission finish time of node C, it will have a very low success rate to get a response from node B, and the throughput of link (A, B) is quite low. When d is longer than 100 m, the situation is similar to what we have discussed in Section 4. In this case, node A can always send at the highest rate, while node C needs to contend with node A after node A finishes its transmission. However, node C can learn the information about the ongoing transmission from the CTS of node B. Therefore, node C can win the channel contention with nearly the same probability as node A. When node C starts the transmission, nodes A and B cannot interfere the transmission so that link (C, D) can achieve a high throughput of 1,300 kilobits per second (Kbps) when d is larger than 100 m. This shows that our power control scheme mitigates the starvation problem of short links in power-controlled schemes.

6.2.2 Random Networks

In this section, we use a randomly deployed network to compare our power control scheme with other schemes. Since TPC-E is focused on energy saving, we excluded it. The experiment is conducted on a 500 m $\times$ 500 m network with 200 randomly deployed nodes. We randomly choose 20 source destination pairs that are apart by more than 250 m. In each experiment, we increase the packet arrival rate for the 20 constant bit rate flows until the throughput gets saturated. The results are averaged over five randomly selected topologies. We evaluate the throughput in three different geographic routing schemes:

- *Routing Scheme 1.* The next-hop node is chosen to be the one that is closest to the destination and is not more than 250 m from the source.
- *Routing scheme 2.* This scheme is similar to scheme 1 but restricts the next-hop node to be within 100 m.
- *Routing scheme 3.* This scheme prefers shorter links. The next-hop node is selected as the closest node to the current transmitter among nodes that provide a positive progress toward the destination.

TABLE 2
Information on Routing Scheme

	Routing I	Routing II	Routing III
Hops per flow	2.03	4.47	10.76
Number of link used	40.6	89.4	215.2
Average link length	172.42m	82.27m	35.71m
Minimal link length	20.04m	22.31m	4.17m
Total path length	7003.91m	7353.29m	7687.99m

Table 2 shows the information of different routing schemes.

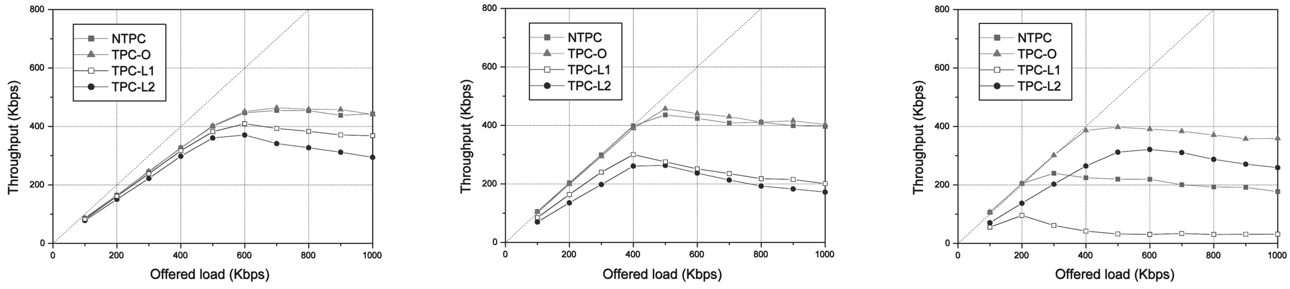
Fig. 6 shows the aggregate end-to-end throughput of different schemes. In routing scheme 1, NTPC and TPC-O give a similar aggregate throughput. They saturated at a total throughput close to 500 Kbps. The throughput of TPC-L1 and TPC-L2 are lower than NTPC and TPC-O. This is because these two schemes cannot prevent collisions, as shown in the string topology. NTPC and TPC-O also have some collisions when the transmission range is close to d_{max}. In this case, the optimal range of the CTS might be larger than d_{max}, as shown in Section 3. Since we restrict the maximal transmission range of CTS, the CTS cannot fully protect a long link. This problem is alleviated in routing scheme 2, where the transmission range is restricted to 100 m. However, the throughput of TPC-L1 and TPC-L2 drops, since they reduce the transmission power for shorter links and make them vulnerable to collisions.

Routing scheme 3 uses shorter links and more hops to deliver the packets. In this scheme, TPC-O provides the best throughput, while TPC-L2 performs close to TPC-O. The throughput of NTPC reduces, since it uses maximal power to reserve the transmission floor, even for a small transmission range. TPC-L1 performs worst, because the full-power CTS can easily corrupt the power-reduced data packet.

Fig. 7 shows that TPC-O also gives the best end-to-end transport throughput, defined as the distance weighted sum of per-flow throughput. Although NTPC also has nearly the same transport throughput in routing schemes 1 and 2, the performance of NTPC is not as good as TPC-O when there are a large number of short links (routing scheme 3). The advantage of TPC-O is that it can work well when there are both long links and short links in the network. The maximal transport throughput in TPC-O for different routing schemes is similar. This verifies our analysis that the network throughput will not change by an order of magnitude for different routing when TPC-O is used.

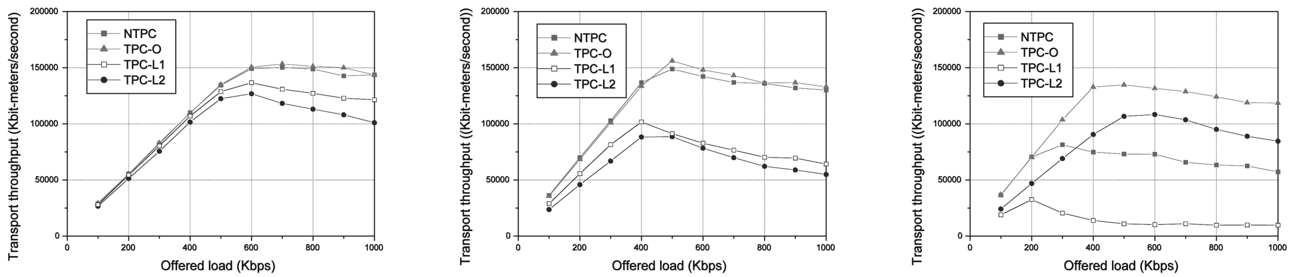
6.3 Transport Throughput with Different Routing Schemes

We further use grid and randomly deployed networks to verify our conjecture that the transmission throughput will not greatly change for different routing schemes. Here, great change means changes proportional to the average link length used in transmission. We compare the performance of the different routing schemes using both uniform and heterogeneous link lengths.



(a) (b) (c)

Fig. 6. Experiment results in random topology: aggregated throughput. (a) Routing scheme 1. (b) Routing scheme 2. (c) Routing scheme 3.



(a) (b) (c)

Fig. 7. Experiment results in random topology: transport throughput. (a) Routing scheme 1. (b) Routing scheme 2. (c) Routing scheme 3.

6.3.1 Uniform Link Length

We first show the transport throughput for different routing schemes when a uniform link length is used. The experiment is conducted on a 480 m $\times$ 480 m grid network. There are 169 nodes placed on a 13 $\times$ 13 square grid with a grid size of 40 m. Each node in the first row/column is a source sending a constant bit rate flow to the corresponding node in the last row/column. Thus, there will be 26 flows (13 horizontal and 13 vertical), each with a total transmission distance of 480 m. We gradually increase the arrival rate of the 26 flows to saturate the network throughput. Routing schemes 1, 2, and 3 use uniform link lengths of 240, 120, and 40 m, respectively.

Fig. 8 shows the throughput under different schemes. Routing scheme 3, which uses shortest link length, gives the largest aggregated throughput. However, decreasing the link distance gives, at best, a 20 percent improvement in the aggregated throughput and not an order of magnitude improvement. Since all flows have the same transmission distance of 480 m, the end-to-end transport throughput is just the aggregated throughput times 480 m for all routing schemes. Thus, the transport throughput of routing scheme 3 also is only 20 percent larger than other schemes. As predicted in Section 3, the routing layer choices will at most affect the throughput by a small constant. Although routing scheme 3 uses six times smaller link lengths, the overall improvement is just 20 percent. This shows that the routing layer plays a minor role in network throughput when optimal power control is used in the MAC layer.

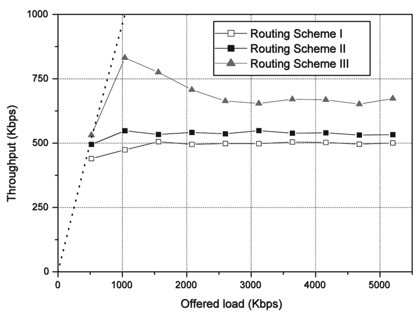
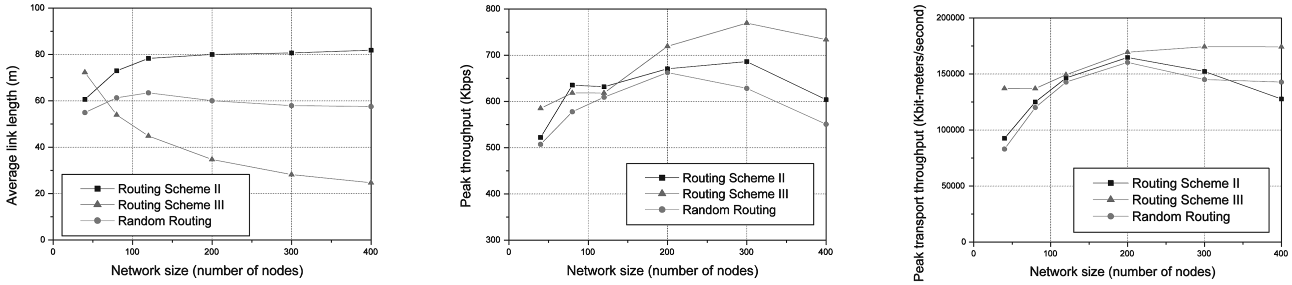


Fig. 8. Aggregated throughput of grid network.

6.3.2 Heterogeneous Link Length

A random network is generated, and heterogeneous link lengths are used in the simulation. To minimize the disturbance of high collision rates when the link length is close to d_{max}, we do not use routing scheme 1. Instead, we compare routing schemes 2 and 3 to a random routing scheme, which randomly chooses a next-hop node that is within 100 m and is closer to the destination.

The network region is a fixed 500 m $\times$ 500 m square, and we increase the number of nodes deployed in the network from 40 to 400. Each node will be randomly selected as either a source or a destination, so there will be 20-200 flows in the network. We average over five different topologies for each network size. As the network density increases, there will be more short links available in the network. The three different routing schemes use different average link lengths in high-density networks (see Fig. 9a). In Fig. 9b, we see that the overall aggregated throughput of the three different routing schemes does not differ by more than 30 percent, while their average link length differs by nearly a factor of 4. If we look at the end-to-end transport throughput (Fig. 9c), once again, we do not see dramatic differences for different routing schemes. We see that as the network size increases, the overall transport throughput increases first and then slowly drops. The increase is



(a) (b) (c)

Fig. 9. Experiment results on random networks of different sizes with optimal power control. (a) Average link length. (b) Aggregated throughput. (c) Transport throughput.

due to the fact there are more flows in the network so that there will be more chances to fully utilize the network space. But, the collision of RTS/CTS messages makes the throughput decrease when the network density becomes extremely high.

7 Conclusion

In this paper, we have investigated the trade-off between transmission power and interference tolerance in distributed MAC systems. Due to this trade-off, the optimal transmission floor area of a link is proportional to the link length in RTS/CTS-based systems. Consequently, the transport throughput is determined by the maximal transmission range rather than the choice of routing protocols. Our analysis shows that the network throughput cannot be improved by more than a constant factor, unless a cooperative MAC [5] or centralized scheduling is used. However, we must be aware of the system complexity and message overhead of such centralized MAC protocols.

Appendix

Multiple Interfering Senders

In the proof of Theorem 1, we only consider a single interfering node. Here, we show that it is enough to increase $d_{int}(j)$ by a constant factor of $(\frac{8}{\alpha-2})^{1/\alpha}$ to prevent collision from multiple interfering nodes when $\alpha > 2$.

We first assume that all interfering nodes are using a transmission power of P_{max}. In this case, interfering nodes have an RTS range of d_{max}, and each interfering node at least takes a transmission floor of $\frac{\pi}{4}d^2_{max}$, as we have shown in Section 4.1. Therefore, the maximum density of interfering nodes is $\frac{4}{\pi d^2_{max}}$ nodes per unit area, and the maximum interference power emitted per unit area is upper bounded by $I = \frac{4P_{max}}{\pi d^2_{max}}$.

When the interfering nodes use a smaller transmission power of $\gamma^\alpha P_{max}$, with $0 < \gamma < 1$, the RTS range of the interfering node is γd_{max}. In this case, the maximum interfering power emitted per unit area is

$$\frac{\gamma^\alpha P_{max}}{\frac{\pi}{4}(\gamma d_{max})^2} = \gamma^{\alpha-2}\frac{4P_{max}}{\pi d^2_{max}}. \tag{37}$$

As we have $0 < \gamma < 1$ and $\alpha > 2$, the interference power emitted per unit area is smaller than $I = 4P_{max}/(\pi d^2_{max})$.

Define $d'_{int}(j) = (\frac{8}{\alpha-2})^{1/\alpha} d_{int}(j)$ as the range that the receiver will send its CTS. We assume that the interfering nodes are uniformly distributed when calculating the cumulated interference outside the range of $d'_{int}(j)$ [27]. Consider a thin ring of r with a width of dr. The interference that comes from this ring is upper bounded by $2\pi r dr \times I$, and the received power at node j will be at most $\frac{2\pi r dr IG}{r^\alpha}$. Summing the interference from all rings, we have the following cumulated interference:

$$\begin{aligned} P_{int} &\leq \int_{d'_{int}(j)}^{\infty} \frac{2\pi r IG}{r^\alpha} dr \\ &= \frac{2\pi IG}{\alpha-2}\left(d'_{int}(j)\right)^{2-\alpha} \\ &= \left(\frac{d'_{int}(j)}{d_{max}}\right)^2 \frac{8P_{max}G}{\alpha-2}\left(d'_{int}(j)\right)^{-\alpha}. \end{aligned} \tag{38}$$

As we have $d'_{int}(j) \leq d_{max}$, we get

$$\begin{aligned} P_{int} &\leq \frac{8P_{max}G}{\alpha-2}\left(d'_{int}(j)\right)^{-\alpha} \\ &= \frac{8P_{max}G}{(\alpha-2)\left(\frac{8}{\alpha-2}\frac{P_{max}d^\alpha_{ij}\beta}{P^{(i)}_t}\right)} \\ &= \frac{P^{(i)}_t G}{d^\alpha_{ij}\beta}. \end{aligned} \tag{39}$$

Thus, the cumulated interference is smaller than $P_{margin}(j)$ when ignoring P_n.

We have shown that setting $d'_{int}(j) = (\frac{8}{\alpha-2})^{1/\alpha} d_{int}(j)$ is enough when $\alpha > 2$. When $\alpha \leq 2$, we can see that the cumulated interference power in (38) is unbounded. This means that the cumulated interference will go to infinity in a large network when $\alpha \leq 2$. However, in most cases, α will be larger than 2 when the distance is larger than a certain threshold.

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