Improving Spatial Reuse through Tuning Transmit Power, Carrier Sense Threshold, and Data Rate in Multihop Wireless Networks

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ABSTRACT

The importance of spatial reuse in wireless ad-hoc networks has been long recognized as a key to improving the network capacity. One can increase the level of spatial reuse by either reducing the transmit power or increasing the carrier sense threshold (thereby reducing the carrier sense range). On the other hand, as the transmit power decreases or the carrier sense threshold increases, the SINR decreases as a result of the smaller received signal or the increased interference level. Consequently, the data rate sustained by each transmission may decrease. This leads naturally to the following questions: (1) How can the trade-off between the increased level of spatial reuse and the decreased data rate each node can sustain be quantified? In other words, is there an optimal range of transmit power/carrier sense threshold in which the network capacity is maximized? (2) What is the relation between the transmit power and the carrier sense threshold? Does increasing the transmit power have the same effect as increasing the carrier sense threshold?

In this paper, we study both problems, and show that (i) in the case that the achievable channel rate follows the Shannon capacity, spatial reuse depends only on the ratio of the transmit power to the carrier sense threshold; and (ii) in the case that only a set of discrete data rates are available, tuning the transmit power offers several advantages that tuning the carrier sense threshold cannot, provided that there is a sufficient number of power levels available. Based on the findings, we then propose a decentralized power and rate control algorithm to enable each node to adjust, based on its signal interference level, its transmit power and data rate. The transmit power is so determined that the transmitter can sustain a high data rate, while keeping the adverse interference effect on the other neighboring concurrent transmissions minimal. Simulation results have shown that, as compared to existing carrier sense threshold tuning algorithms, the proposed power and rate control algorithm yields higher network capacity.

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Categories and Subject Descriptors

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Theory, Algorithms, Performance

Keywords

Spatial reuse, wireless ad-hoc networks, power control, carrier sense threshold.

1. INTRODUCTION

Multihop wireless networks have gained tremendous attention in recent years because of their wide civilian and military applications and their capability of building networks without the need for a pre-existing infrastructure. One important performance metric in such networks is the network capacity, i.e., the number of bits that can be transported simultaneously in the network. The network capacity depends on the achievable channel capacity at each individual wireless link and the level of *spatial reuse* — the total number of concurrent transmissions that can be accommodated in the network [2].

Although increasing the number of concurrent transmissions helps with the network capacity, there is a counter effect to arbitrarily increasing this number. This is because the wireless medium is essentially *shared* among nodes, and signals that arrive at a receiver from other concurrent transmissions, albeit attenuated, will be taken as interference by the receiver. Because the quality of a wireless link and consequently its achievable rate are largely characterized by the Signal-to-Interference-and-Noise-Ratio (*SINR*) at the receiver, concurrent transmitters should be well separated from each other to ensure an acceptable SINR. This implies that there exists a tradeoff between the level of spatial reuse and the data rate that can be sustained by each transmission.

To ensure an adequate level of spatial reuse, IEEE 802.11 MAC has employed *physical carrier sensing* [2, 4, 5, 6]. Under physical carrier sensing, whenever a wireless node intends to transmit, it first senses the medium. Only when the signal strength sampled is below the *Carrier Sense Threshold*, T_{cs}, will the node initiate the transmission [7]. Because the transmitted radio signal attenuates with the distance, the carrier sense threshold effectively determines the minimum distance, termed as the *carrier sense range* [2], between any pair of transmitters. An analysis of the impact of the carrier sense range on the network capacity has been presented in [2, 5]. Based on the analytical results, a spatial backoff algorithm that dynamically tunes both the carrier sense threshold and the data rate has been proposed in [3].

What has not been fully explored (perhaps except in [20]) is the other *control knob(s)* that may determine the minimum distance between concurrent transmitters for spatial reuse. Recall that the wireless medium is shared, and the *sharing range* is determined by *both* the transmit power and the carrier sense threshold each wireless node uses[1]. One can increase the level of spatial reuse by either reducing the transmit power or increasing the carrier sense threshold (thereby reducing the carrier sense range). This leads naturally to the following questions: What is the relation between the transmit power and the carrier sense threshold? Does increasing the transmit power have the same effect of increasing the carrier sense threshold? Once these questions are answered, one can then proceed to quantify the trade-off between the increased level of spatial reuse and the decreased data rate each node can sustain (because of the decrease in the SINR).

In this paper, we aim to answer the above questions in an analytical framework. Specifically, our contributions are

- Based on the analytic models in [1, 26], we express the network capacity as a function of the transmit power P_{tx} and the carrier sense threshold T_{cs}, under the assumptions that the network is densely populated (so as to consider the worst-case interference scenario) and wireless nodes are uniformly and independently distributed in a region U. For ease of analysis, the Shannon capacity under the Additive White Gaussian Noise (AWGN) channel model is used to characterize the relation between the channel rate and the SINR. The analysis shows that spatial reuse depends *only* on the ratio of P_{tx} to T_{cs}. This implies that to improve the network capacity one can tune one parameter, while fixing the other at an appropriate value.
- While the analytical model assumes that the achievable channel rate is a continuous function of SINR (with the use of the Shannon capacity), there are only a number of data rates available in reality. Ideally given the SINR, a wireless node chooses the maximal data rate that can be sustained. We show that, *under the case of a discrete number of channel rates*, tuning the transmit power offers several advantages that tuning the carrier sense threshold cannot offer, *provided that there is a sufficient number of power levels available.*
- Based on the above findings, we devise a *localized* power and rate control algorithm, called *PRC*, that enables each transmitter to adapt to the interference level that it perceives and determines its transmit power and data rate. The transmit power is so determined that the transmitter can sustain the highest possible data rate, while keeping the adverse interference effect on the other neighboring concurrent transmissions minimal. Simulation results have shown that, as compared to existing carrier sense threshold tuning algorithms, PRC gives higher network capacity. The performance improvement is as much as up to 22%.

The remainder of the paper is organized as follows. In Section 2, we summarize related work in the literature and highlight the major difference between existing work and our work. In Section 3, we derive the network capacity as a function of transmit power and carrier sense threshold and draw several important conclusions from the derivation. In Section 4, we show that in the case that only a discrete number of data rates are available, tuning the transmit power offers several advantages that tuning the carrier sense threshold cannot. Following that, we present in Section 5 the proposed PRC algorithm along with its theoretical base, and carry out a simulation study to evaluate it in Section 6. Finally, we conclude this paper in Section 7 with a list of future research avenues.

2. RELATED WORK

We summarize related work in the following categories: carrier sense threshold adjustment, power control, and analysis of the relation between the two parameters.

Carrier sense threshold adjustment:. A number of studies have been carried out on spatial reuse that employs IEEE 802.11 physical carrier sensing. In these studies, the level of spatial reuse is controlled by varying the carrier sense threshold. The impact of the carrier sense threshold on the network capacity has been investigated in [1, 2, 4, 5]. Given a predetermined transmission rate, Zhu *et al.* [4] determine the optimal carrier sense threshold that maximizes spatial reuse for several regular topologies. Based on the *SINR* required to sustain a predetermined transmission rate, Zhu *et al.* propose in [5] a dynamic algorithm that adjusts the carrier sense threshold to maximize spatial reuse. Vasan, Ramjee, and Woo [6] propose an algorithm, called *echos*, to dynamically adjust the carrier sense threshold in order to allow more flows to co-exist in 802.11-based hotspot wireless networks. Nadeem *et al.* [9] propose a *Location En-*

[1]in addition to other environmental factors (such as multipath fading, shadowing, temperature and humidity variation, and existence of obstacles in between).

hanced DCF algorithm that exploits location information to improve spatial reuse for pre-defined transmission rates. Yang and Vaidya [1] are perhaps the first to address, with the data rate issue figured in, the impact of physical carrier sense on spatial reuse in multi-hop wireless networks. They also propose a heuristic algorithm, called *Dynamic Spatial Backoff (DSB)*, that dynamically adjusts, based on consecutive successful/failed transmissions, both the carrier sense threshold and the transmission rate [3]. By default, each transmission rate is associated with a carrier sense threshold such that a node is expected to transmit successfully at the rate using the carrier sense threshold. If a transmitter successfully transmits frames for a pre-determined number of times, it increases its data rate to the next higher rate and the current carrier sense threshold is associated with the new transmission rate. On the other hand, if a transmitter encounters transmission failures for a pre-determined number of times, it decreases the carrier sense threshold to a next lower one (in the case that currently it uses higher carrier sense threshold than the default one associated with current transmission rate) or decreases its transmission rate to a next lower one and uses the carrier sense threshold associated with the transmission rate (in the case that currently it uses the same carrier sense threshold as the default one associated with current transmission rate).

Power control:. The issue of power control has been studied in the context of *topology maintenance*, where the objective is to preserve network connectivity, reduce power consumption, and mitigate MAC-level interference [11, 12, 13, 14, 15, 16]. Use of power control for the purpose of spatial reuse and capacity optimization has been treated in the *PCMA* protocol [10], the *PCDC* protocol [17], and the *POWMAC* protocol [18]. Monks *et al.* [10] propose *PCMA* in which the receiver advertises its interference margin that it can tolerate on an out-of-band channel and the transmitter selects its transmit power that does not disrupt any ongoing transmissions. Muqattash and Krunz also propose *PCDC* and *POWMAC* in [17, 18] respectively. The *PCDC* protocol constructs the network topology by overhearing RTS and CTS packets, and the computed interference margin is announced on an out-of-band channel. The *POWMAC* protocol, on the other hand, uses a single channel for exchanging the interference margin information. All these protocols do not consider the effect of carrier sense threshold on the network capacity even though it is a major determinant for spatial reuse.

The issue of jointly tuning the transmit power and the data rate has been recently addressed in [20] in the context of over-populated wireless hotspots. With the objective of mitigating interference and improving user throughput, the authors extend the *auto rate fallback* scheme (used in IEEE 802.11) to *power auto rate fall back* (*PARF*) and *power estimated rate fallback* (*PERF*). The basic idea is to increase the power level after failing to send frames with the minimum data rate a pre-determined number of times. Similarly, the power level is decreased after successfully transmitting a pre-determined number of frames with the maximal data rate.

Analysis of the relation between the transmit power and the carrier sense threshold:. Fuemmeler *et al.* [8] also analyze the relation between the transmit power and the carrier sense threshold in determining the network capacity. They conclude that transmitters should keep the product of their transmit power and carrier sense threshold fixed at a constant, i.e., the lower the transmit power, the higher the carrier sense threshold (and hence the smaller the carrier sense range), and vice versa. A combination of lower transmit power and higher carrier sense leads to a large number of concurrent transmissions, with each transmission sustaining a small data rate. On the other hand, a combination of higher transmit power and lower carrier sense threshold leads to a small number of concurrent transmissions, with each transmission sustaining a large data rate. Although the analysis gives a general trend, it does not give guidelines on how to select the two parameters to *maximize* the network capacity. In contrast, our analysis (Section 3) shows that the network capacity depends only on the *ratio* of the transmit power to the carrier sense, and there exists a (P_{tx}, T_{cs}) region in which the network capacity is optimized.

3. NETWORK CAPACITY AS FUNCTION OF TRANSMIT POWER AND CARRIER SENSE THRESHOLD

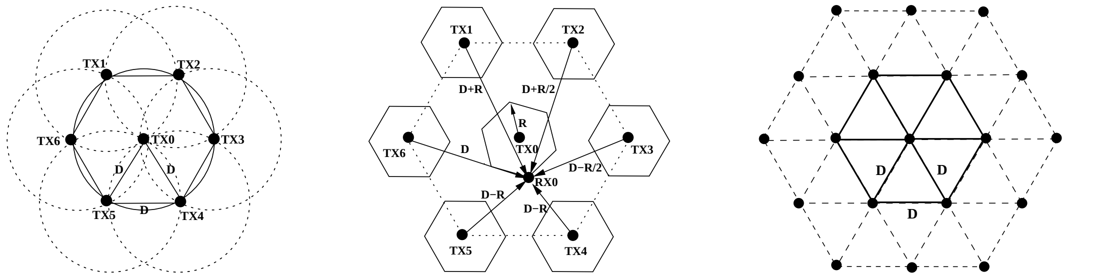
In this section, we investigate how the transmit power and the carrier sense threshold impact the network capacity. One can increase the level of spatial reuse by either reducing the transmit power or increasing the carrier sense threshold (thereby reducing the carrier sense range). On the other hand, as the transmit power decreases or the carrier sense threshold increases, the SINR decreases as a result of the smaller received signal or the increased interference level. Consequently, the receiver may not be able to correctly decode the symbol and the data rate sustained by each transmission may decrease. This leads naturally to the following questions: (1) How can the trade-off between the increased level of spatial reuse and the decreased data rate each node can sustain (because of the decrease in the SINR) be quantified? In other words, is there an optimal range of transmit power/carrier sense threshold in which the network capacity is maximized? (2) What is the relation between the transmit power and the carrier sense threshold? Does increasing the transmit power have the same effect of increasing the carrier sense threshold? We will study both problems in this section.

3.1 Interference Model

We assume that nodes are distributed uniformly and independently in an area of U with reasonably high node density λ (so as to account for worst-case interference). We use the path-loss radio propagation model given below to characterize path loss.

$$P_{rx} = \frac{P_{tx}}{R^{\theta}}, \tag{1}$$

where P_{tx} and P_{rx} are, respectively, the transmit power at the transmitter and the received signal strength at the re-



(a) 1^{st} tier concurrent transmissions (b) 1^{st} tier interfering nodes (c) Area consumed in one transmission

Figure 1: Interference Model (by courtesy of [1]).

ceiver, R is the distance between the transmitter and the receiver, and θ is the path loss exponent, ranging from 2 (line of sight free space) to 4 (indoor) [22]. We assume a perfect MAC protocol so that each communication channel is fully utilized.

We first derive the interference level and the SINR at a receiver. Let the carrier sense range be denoted as D, when the transmit power and the carrier sense threshold are set, respectively, to P_{tx} and T_{cs}. Consider the transmission between a transmitter TX_0 and a receiver RX_0 that are of distance R away from each other. With physical carrier sense, when TX_0 intends to transmit, all the nodes within D have to be detected silent. The situation is depicted in the Honey-grid model [23] in Figure 1. As shown in Figure 1 (a), nodes that are concurrently transmitting (with transmit power P_{tx}) at the same time as a source node TX_0 does, must be at least of distance D away from TX_0 and each other. Transmission activities of these nodes will interfere with that of TX_0 and contribute to the interference level perceived at the corresponding receiver RX_0. Let the concurrently transmitting nodes that are of distance iD ($i \geq 1$) away from TX_0 be denoted as the i^{th} tier interfering nodes of TX_0. For example, as illustrated in Fig. 1 (b), there are at most six 1^{st} tier interfering nodes. It has been verified that the interference contributed by the 1^{st} tier interfering nodes (as perceived at the receiver) is of the same order as the total, accumulated interference from the entire network [24]. As such, we will henceforth neglect the interference that results from the 2^{nd} and higher-tier interfering nodes.

As shown in [26] (in the context of cell planning in cellular networks) and in [1] (in the context of wireless multi-hop network), the worst case interference occurs when the receiver RX_0 is so positioned that the six 1^{st} tier interfering nodes are, respectively, of distance $D-R$, $D-R$, $D-R/2$, D, $D+R/2$, and $D+R$ away from it, as illustrated in Figure 1 (b). The worst-case interference, I, as perceived at RX_0 can then be expressed as

$$I = \frac{2P_{tx}}{(D-R)^\theta} + \frac{P_{tx}}{\left(D-\frac{R}{2}\right)^\theta} + \frac{P_{tx}}{D^\theta} + \frac{P_{tx}}{\left(D+\frac{R}{2}\right)^\theta} + \frac{P_{tx}}{(D+R)^\theta}. \tag{2}$$

The corresponding worst-case $SINR$ at the receiver RX_0 can be expressed as[2]

$$\begin{aligned} SINR & \\ &= \frac{\frac{P_{tx}}{R^\theta}}{\frac{2P_{tx}}{(D-R)^\theta} + \frac{P_{tx}}{\left(D-\frac{R}{2}\right)^\theta} + \frac{P_{tx}}{D^\theta} + \frac{P_{tx}}{\left(D+\frac{R}{2}\right)^\theta} + \frac{P_{tx}}{(D+R)^\theta}} \\ &= \frac{1}{\frac{2}{\left(\frac{D}{R}-1\right)^\theta} + \frac{1}{\left(\frac{D}{R}-\frac{1}{2}\right)^\theta} + \frac{1}{\left(\frac{D}{R}\right)^\theta} + \frac{1}{\left(\frac{D}{R}+\frac{1}{2}\right)^\theta} + \frac{1}{\left(\frac{D}{R}+1\right)^\theta}} \\ &\triangleq f\left(\frac{D}{R}\right). \end{aligned} \tag{3}$$

where $f(x)$ is an increasing function over x.

3.2 Network Capacity as a Function of Transmit Power and Carrier Sense Threshold

Given a certain level of $SINR$, we express the achievable channel rate, Γ_c, with *Shannon capacity* under the additive white Gaussian noise channel model [25]. That is,

$$\Gamma_c = W \cdot log_2\left(1 + SINR\right), \tag{4}$$

where W is the channel bandwidth in hertz.

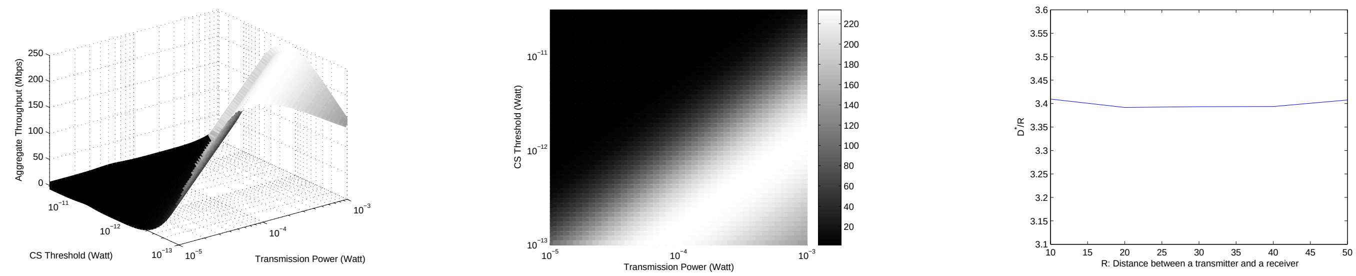
After relating the achievable channel rate with the interference level (which is, in turn, affected by the carrier sense range D and the transmission range R), we are now in a position to "count" how many concurrent transmissions are allowed under physical carrier sense in an area of U. Under the assumption of a reasonably populated network, the transmitters that can transmit concurrently will be positioned as shown in Figure 1 (c). As (i) each three transmitters *shares* a regular triangular with side length of D and (ii) every transmitter is the apex of six such triangles, each transmitter *consumes* an area of $U_A = \sqrt{3}D^2/2$ (with the boundary effect ignored). The network capacity, Γ_n, can then be expressed as

$$\Gamma_n = \Gamma_c \cdot \frac{U}{U_A}, \tag{5}$$

where $\frac{U}{U_A}$ is the total number of concurrent transmissions under physical carrier sense. Substituting $U_A = \sqrt{3}D^2/2$ and Eq. (4) into Eq. (5), we have

$$\Gamma_n = \frac{C_0}{D^2} \cdot log_2\left(1 + f\left(\frac{D}{R}\right)\right), \tag{6}$$

[2]Note that we ignore the background noise in the expression.



(a) Network capacity as a function of P_{tx} and T_{cs} (b) Optimal ratio between CS Threshold and Power (c) Ratio between D^* and R

Figure 2: Existence of optimal carrier sense range.

where $C_0 \triangleq \frac{2\sqrt{3}\cdot W\cdot U}{3}$ is a constant. Now given the fact that the carrier sense range D is expressed as $D = \left(\frac{P_{tx}}{T_{cs}}\right)^{\frac{1}{\theta}}$, Eq. (6) can be expressed as a function of P_{tx} and T_{cs}:

$$\Gamma_n = C_0 \cdot \left(\frac{T_{cs}}{P_{tx}}\right)^{\frac{2}{\theta}} \cdot log_2\left(1 + f\left(C_1 \cdot \left(\frac{P_{tx}}{T_{cs}}\right)^{\frac{1}{\theta}}\right)\right), \quad (7)$$

where $C_1 \triangleq \frac{1}{R}$ is a constant.

Figure 2 depicts Γ_n as a function of P_{tx} and T_{cs}. As shown in Figure 2 (b), the network capacity only depends upon the ratio of P_{tx} to T_{cs} and is maximized when the combination of P_{tx} and T_{cs} fall in the white stripe. This indicates that the best value of D can be determined by adjusting P_{tx} (or T_{cs}), while fixing the other parameter. Note that given a fixed value of P_{tx}, Eq. (7) reduces to the model derived in [2]. Figure 2 (c) shows that the ratio between D^*, which achieves the maximal Γ_n, and R. It is observed that the ratio keeps a value of about 3.4 over various R.

4. ANALYSIS ON WHICH PARAMETER TO TUNE

In Section 3, we showed that, *under the case that the achievable channel rate is a continuous function of SINR*, the network capacity depends only upon $\frac{P_{tx}}{T_{cs}}$. (Recall that in Eq. (6) we use the *Shannon* capacity to denote the achievable channel rate given the SINR.) This implies that, to improve (or in the best case optimize) network capacity, one can tune one parameter, while fixing the other at an appropriate value. This leads naturally to the question that which parameter should be tuned.

In the current practice, the carrier sense threshold can be essentially set in the PHY/MAC layers to any value, while there are only a fixed number of power levels available. Based on this observation, one may be tempted to believe that it is more flexible to tune the carrier sense threshold. In this section, we show that, *under the case that there are a fixed number of channel rates* (e.g., IEEE 802.11), while the relation between P_{tx} and T_{cs} essentially remain unchanged, tuning the transmit power offers several advantages that tuning the carrier sense threshold cannot.

4.1 Two Examples that Show Benefits of Power Control

In this section, we give two specific examples in which there is a definite advantage of tuning the transmit power. We consider the case that there are a fixed number, K, of data rates available $\{r[i], 1 \leq i \leq K\}$. $r[i] \leq r[j]$ if $i \leq j$ ($i, j \in [1, K]$). Let the SINR threshold required to support a data rate of $r[i]$ be denoted as $SINR^{th}_{r[i]}$, i.e., $[SINR^{th}_{r[i]}, SINR^{th}_{r[i+1]})$ is the range for data rate $r[i]$. (As shown in Table 1 [19], the SINR must exceed certain threshold in order to support the corresponding data rate.)

Example 1:. Consider the transmission between the transmitter TX and the receiver RX (which is apart from TX by a distance of R). For ease of exposition, we assume that all the nodes use the same transmit power P_{tx}. Let M denote the number of concurrent transmissions at the time TX transmits. Note that M is a function of T_{cs} – the larger T_{cs}, the larger the value of M. The *SINR* at the receiver RX is then

$$SINR_{RX} = \frac{P_{tx}/R^\theta}{\sum_{k=1}^{M} P_{tx}/R_k^\theta} = \frac{\frac{1}{R^\theta}}{\sum_{k=1}^{M}\frac{1}{R_k^\theta}}, \quad (8)$$

where R and R_k are the distance from RX to TX and to an interfering node k, respectively. Note that the only term in Eq. (8) that T_{cs} can affect is the term $\sum_{k=1}^{M}\frac{1}{R_k^\theta}$ (or specifically the value of M).

Without loss of generality, assume that $SINR_{RX}$ falls between $SINR^{th}_{r[i]}$ and $SINR^{th}_{r[i+1]}$ so that the receiver RX can sustain a data rate of $r[i]$. Since RX can only sustain the data rate $r[i]$ and its $SINR_{RX}$ is higher than $SINR^{th}_{r[i]}$, it may determine to decrease $SINR_{RX}$ to $SINR^{th}_{r[i]}$, in the hope that more concurrent transmissions can be accommodated. If T_{cs} is the control knob, TX then increases its T_{cs} level and allows the interference level to increase, so long as its $SINR_{RX}$ is above $SINR^{th}_{r[i]}$ (perhaps with a safe margin). This attempt may, however, *not* succeed, because of the following reasons. By increasing T_{cs}, the carrier sense range D reduces. On the one extreme, there may not be any node that attempts transmission *and* lies within the original carrier sense range. In this case, $SINR_{RX}$ does not decrease. On the other extreme, there may be one or

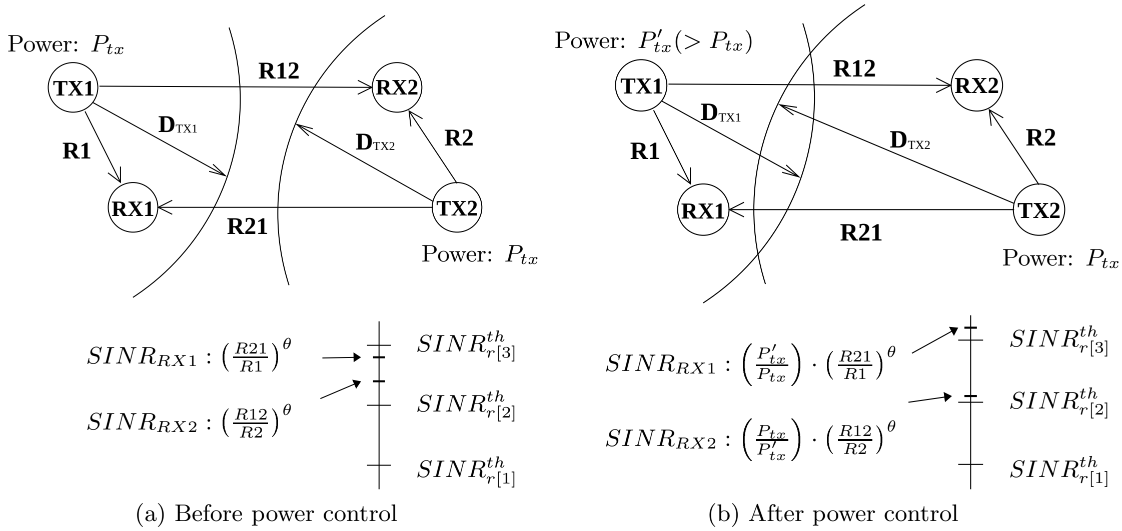


Figure 3: An example that illustrates the benefit of power control.

Table 1: For BERs less than or equal to 10^{-5}, the minimum *SINR* required to support the corresponding data rate.

Rates (Mbps)	$SINR$ (dB)	Modulation	Coding Rate
54	24.56	64-QAM	3/4
48	24.05	64-QAM	2/3
36	18.80	16-QAM	3/4
24	17.04	16-QAM	1/2
18	10.79	QPSK	3/4
12	9.03	QPSK	1/2
9	7.78	BPSK	3/4
6	6.02	BPSK	1/2

more nodes which will be included in, and contribute to the term $\sum_{k=1}^{M} \frac{1}{R_k^{\theta}}$ after the increase in T_{cs}. The amount of contribution may, however, be so large that $SINR_{RX}$ falls below $SINR^{th}_{r[i]}$. The probability that either event occurs depends very much on the node density and the traffic distribution, both of which are not under the control of carrier sense threshold.

Now we consider the same scenario but with the use of power control. Let the transmit power used by the transmitter TX be denoted as P'_{tx} and assume that other concurrent transmitters use P_{tx}. $SINR_{RX}$ at the receiver RX can be expressed as

$$SINR_{RX} = \frac{P'_{tx}/R^{\theta}}{\sum_{k=1}^{M} P_{tx}/R_k^{\theta}}. \tag{9}$$

If through some feedback mechanism, the transmitter TX is aware of the fact that $SINR_{RX}$ exceeds $SINR^{th}_{r[i]}$, it may well adjust its transmit power to achieve the desirable SINR level (i.e., $SINR^{th}_{r[i]}$). The key issue is that a sufficient number of power levels must be available in order to provide fine granularity of control.

Example 2:. Consider the case that both the transmitters TX_1 and TX_2 are transmitting simultaneously to their corresponding receivers RX_1 and RX_2. Initially both transmitters use the transmit power P_{tx}. Without loss of generality, assume that the SINR perceived at both receivers allows them to sustain the data rates at $r[2]$ (Figure 3). Now TX_1 exercises power control and (judiciously) increases its transmit power to P'_{tx}, so that it sustains a higher data rate $r[3]$ while not depriving the other concurrent transmission $TX_2 \rightarrow RX_2$ of the data rate $r[2]$. That is, the power increase $(P'_{tx} - P_{tx})$, albeit its adverse effect on $SINR_{RX_2}$, does not make $SINR_{RX_2}$ to fall below $SINR^{th}_{r[2]}$. As shown in Figure 3 (b), the net effect of TX_1's increasing its transmit power as perceived at RX_2 is that TX_2's carrier sense range is increased.

Now we investigate whether or not the same objective (of increasing the data rate of one transmission without deteriorating that of the other transmission) can be achieved by tuning the carrier sense threshold. With the method of tuning carrier sense threshold, $SINR_{RX_1}$ can increase only by decreasing T_{cs} to the degree that TX_2 is included within the carrier sense range of TX_1. In this case, when TX_1 transmits, TX_2 will be silenced. This implies that, in order for $TX_1 \rightarrow RX_1$ to sustain a higher data rate, the data rate of $TX_2 \rightarrow RX_2$ has to be reduced to zero!

5. PROPOSED POWER AND RATE CONTROL ALGORITHM

Recall that in Section 3 we showed that the network capacity depends only upon $\frac{P_{tx}}{T_{cs}}$, and the maximum network capacity can be achieved by tuning one parameter while fixing the other at an appropriate value. In Section 4, we argued that tuning the transmit power offers more advantages than tuning the carrier sense threshold, so long as the number of power levels available for tuning is sufficient. Based on the above findings, we devise in this section a *localized* power

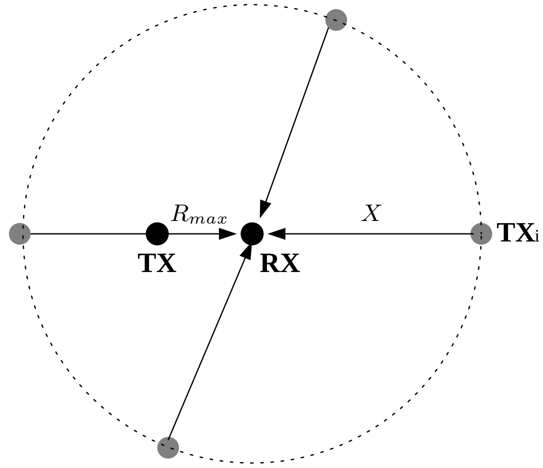


Figure 4: Possible locations of a source causing the same amount of interference to RX

and rate control algorithm that enables each transmitter to adapt to the interference level that it perceives and determines its transmit power. The transmit power is so determined that the transmitter can sustain the highest possible data rate, while keeping the adverse interference effect on the other neighboring concurrent transmissions minimal. In what follows, we will first discuss how to determine a power range (Section 5.1) and an adequate carrier sense threshold (Section 5.2). Then we elaborate on the theoretical base, and the method which each transmitter uses, for power and rate control (Section 5.3).

5.1 Determining Power Range

We first determine the minimum transmit power that ensures that the receiver can sustain the minimum data rate. Consider the worst-case scenario in which TX_0 transmits with the minimum transmit P^{min}, while its six 1^{st} tier interfering nodes transmit with the maximum power level P^{max}. Then, the SINR level at RX_0 is $\frac{P^{min}}{P^{max}} \cdot SINR$, where $SINR$ is given in Eq. (3). To ensure that the receiver can sustain the minimum data rate, we enforce

$$\frac{P^{min}}{P^{max}} \cdot SINR \geq SINR^{th}_{r[1]}. \tag{10}$$

Eq. (10) implies that

$$P^{min} \geq \frac{SINR^{th}_{r[1]}}{SINR} \cdot P^{max}. \tag{11}$$

Setting $SINR^{th}_{r[1]} = 6.02$ dB (Table 1) and $SINR = 10.2531$ (obtained by subtituting the optimal ratio $\frac{D}{R} = 3.4$ (Figure 2 (c)) into Eq. (3)) in Eq. (10), we have $P^{min} = 0.39 \cdot P^{max}$.

5.2 Determining Carrier Sense Threshold

We determine an adequate carrier sense threshold T_{cs} that will be used by all the nodes (and remain unchanged throughout the network operation phase). Consider the transmission between the transmitter TX and the receiver RX (which is apart from TX by the maximum transmission range of R_{max}). Let $P^{min}_{tx}(= P^{min})$ the minimum transmit power for TX. Each node sets its carrier sense threshold T_{cs} such that if a transmitter transmits with P^{min}_{tx} at a distance of R_{max}, the minimal data rate of $r[1]$ can be sustained. Specifically, for RX to sustain the minimal data rate $r[1]$, the level of SINR at RX should not be less than $SINR^{th}_{r[1]}$, i.e.,

$$\frac{P^{min}_{tx}/R^{\theta}_{max}}{I_{RX}} \geq SINR^{th}_{r[1]}, \tag{12}$$

where I_{RX} is the interference level perceived at RX. Rearranging Eq. (12), we have

$$I_{RX} \leq \frac{P^{min}_{tx}}{R^{\theta}_{max} \cdot SINR^{th}_{r[1]}}. \tag{13}$$

Now we need to determine T_{cs} *at the transmitter* to ensure that Eq. (13) is satisfied *at the receiver*. The major difficulty here is that the transmitter does not know I_{RX} in Eq. (13). Nor can it infer accurately from its own interference level I_{TX}. This is because the interference levels perceived at the transmitter and at the receiver depend very much on the locations of all the concurrent transmissions relative to those of the transmitter and the receiver, and may differ significantly. Hence we decide to be *conservative*, and set T_{cs} to the *minimal* possible value when RX perceives an interference level of I_{RX}. As shown in Figure 4, the *most conservative* scenario occurs when I_{RX} is contributed by a single interfering node TX_i that is on the (extended) line $TX - RX$, is located in the opposite direction of TX, and is of distance X away from RX. In this case, X is minimized when TX_i uses its minimum transmit power P^{min}. Substituting $I_{RX} = \frac{P^{min}}{X^{\theta}}$ into Eq. (13) we have

$$X \geq (SINR^{th}_{r[1]})^{\frac{1}{\theta}} \cdot R_{max}. \tag{14}$$

The minimum interference level perceived at TX can then be expressed as

$$\begin{aligned} I_{TX} &= \frac{P^{min}}{(X + R_{max})^{\theta}} \\ &\leq \frac{P^{min}}{\left(\left(SINR^{th}_{r[1]}\right)^{\frac{1}{\theta}} R_{max} + R_{max}\right)^{\theta}} \\ &= \frac{P^{min}}{R^{\theta}_{max} \cdot \left(1 + \left(SINR^{th}_{r[1]}\right)^{\frac{1}{\theta}}\right)^{\theta}}. \end{aligned} \tag{15}$$

If we set T_{cs} to $\frac{P^{min}}{R^{\theta}_{max} \cdot \left(1 + \left(SINR^{th}_{r[1]}\right)^{\frac{1}{\theta}}\right)^{\theta}}$ at the transmitter, i.e., the transmission will not be initiated unless the received signal strength is below $\frac{P^{min}}{R^{\theta}_{max} \cdot \left(1 + \left(SINR^{th}_{r[1]}\right)^{\frac{1}{\theta}}\right)^{\theta}}$, then we ensure the interference level perceived at the receiver is at most $\frac{P^{min}_{tx}}{R^{\theta}_{max} \cdot SINR^{th}_{r[1]}}$ and that the receiver can sustain the minimal data rate.

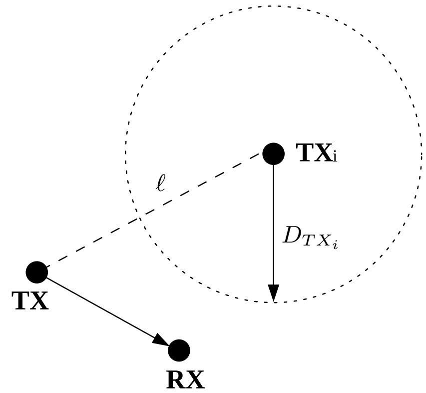


Figure 5: Constraint on the transmit power based on the estimated distance, ℓ, between TX and an interfering node TX_i.

5.3 Proposed Power and Rate Control Algorithm

When a node intends to transmit, if the interference level perceived is below T_{cs}, the node needs to determine the transmit power level. The T_{cs} value calculated in the previous section ensures that the receiver can sustain the minimal data rate, if the transmitter transmits with the minimal transmit power P_{tx}^{min}. The transmitter can increase its transmit power to sustain a lager data rate. However, the increase in the power level should not be so significant that it deprives the other concurrent transmissions of sustaining their minimal data rates. Finding such a maximal *allowable* increase in the transmit power requires global knowledge of the SINRs of all the receivers, which is very difficult, if not impossible, in real, dynamic environments. Thus we propose to estimate such a range based *only* on the interference level at the transmitter.

Theoretical base:. Assume that at the time of attempting for transmission, TX detects its interference level I_{TX} to be below T_{cs}. Although I_{TX} may be contributed by multiple, concurrent transmissions, we assume (again) the most conservative scenario, i.e., the interference is contributed by a single interfering node TX_i that is of distance ℓ from TX (Figure 5). By making such a conservative assumption, we will be able to infer the worst-case, adverse impact of having TX transmit with P_{tx} on the transmission initiated by TX_i. The minimal value of the distance ℓ can be obtained when TX_i is assumed (again with a conservative view) to transmit with the minimal power $P_{TX_i}^{min}$, i.e., $\ell_{min} = \left(\frac{P_{TX_i}^{min}}{I_{TX}}\right)^{\frac{1}{\theta}}$.

The carrier sense range at node TX_i, D_{TX_i}, when TX_i uses the carrier sense threshold T_{cs} and TX transmits with P_{tx}, is given by $\left(\frac{P_{tx}}{T_{cs}}\right)^{\frac{1}{\theta}}$. To ensure both TX and TX_i can engage in transmission concurrently, we have to enforce $D_{TX_i} \leq \ell_{min}$, i.e.,

$$\left(\frac{P_{tx}}{T_{cs}}\right)^{\frac{1}{\theta}} \leq \left(\frac{P_{TX_i}^{min}}{I_{TX}}\right)^{\frac{1}{\theta}}. \tag{16}$$

As $P_{TX_i}^{min} \geq P^{min}$, we further "tighten" the bound on P_{tx} (by erring on the conservative side) as

$$P_{tx} \leq \frac{T_{cs}}{I_{TX}} \cdot P^{min} \triangleq P_{tx}^{est}. \tag{17}$$

Note that P_{tx}^{est} is inversely proportional to I_{TX}. This means that if TX perceives a small level of I_{TX}, it can transmit with a higher power level and vice versa. Since the transmit power can not exceed the maximal power P^{max} that a hardware allows, we enforce the following:

$$P_{tx}^{min} = P^{min} \leq P_{tx} \leq \min\{P^{max}, P_{tx}^{est}\} \triangleq P_{tx}^{max}, \tag{18}$$

where P_{tx}^{est} is calculated in Eq. (17). Note that all the items needed for calculating P_{tx}^{est} are readily available at the transmitter.

Proposed power and rate control algorithm:. Recall that P_{tx}^{est} is derived under the conservative scenario in which the interference level, I_{TX}, perceived at TX is solely contributed by a closest possible interfering node. The interference level I_{TX} is then used to determine P_{tx}^{est}, with the objective of not throttling the transmission at the closest possible interfering node. To go one step further, if the data rate afforded by P_{tx}^{max} can be achieved with a smaller power level, there is no need to transmit with P_{tx}^{max}. Instead, a smaller transmit power that sustains the same data rate can be used, in the hope that the interference level perceived at the other interfering nodes can be mitigated and higher data rates can be sustained by the concurrent transmissions.

To achieve the above objective, we propose a localized algorithm, called *Power and Rate Control* (PRC). Conceptually, each transmitter finds the maximal SINR level, $SINR_{RX}^{max}$, that can be achieved at the receiver RX with the transmit power P_{tx}^{max}. This can be realized by having the receiver piggyback (in the frame header) its perceived interference level I_{RX}. If $SINR_{r[i+1]}^{th} > SINR_{RX}^{max} \geq SINR_{r[i]}^{th}$, then $r[i]$ is the maximal data rate that can be sustained. The transmitter then uses the data rate $r[i]$ for transmission. Moreover, it sets the transmit power P_{tx} such that RX can sustain the level of $SINR_{r[i]}^{th}$, i.e.,

$$\frac{P_{tx}/R^{\theta}}{I_{RX}} = SINR_{r[i]}^{th}, \tag{19}$$

or

$$P_{tx} = SINR_{r[i]}^{th} \cdot I_{RX} \cdot R^{\theta}. \tag{20}$$

Note that in the case that $SINR_{RX}^{max}$ is smaller than $SINR_{r[1]}^{th}$, we set both P_{tx} and the data rate to zero.

The pseudo code of PRC is given below. The PRC algorithm commences when a node is in the *standby mode*, where the node intends to initiate a transmission and monitors its interference level. If the interference level falls under T_{cs}, the node invokes PRC to determine the transmit power and the data rate, and then start the transmission.

Due to the fact that concurrent transmissions may commence and terminate dynamically, the interference level perceived at the receiver fluctuates with time. Hence each transmitter needs to adjust, based on the interference level, its transmit power and data rate dynamically. To monitor the variation in the interference level, we define two thresholds N_s^{th} and N_f^{th}, respectively for consecutive successful transmissions and failures. Each transmitter keeps track of the number of consecutive successful transmissions and failures, N_s and N_f. When N_s or N_f crosses the corresponding threshold N_s^{th} or N_f^{th}, the transmit power and data rate are adjusted by *PRC*.

Note that if *PRC* cannot determine an adequate combination of the transmit power and the data rate, the current transmission is deferred. It is also worth mentioning that if the interference level stabilizes (e.g.,the number of concurrent transmissions remains unchanged), the transmit power and the data rate determined in each invocation of *PRC* will be the same, since they are determined based only on the the interference level.

Algorithm 1 Power and Rate Control (PRC)

$P_{tx} \leftarrow 0$ and $r_{tx} \leftarrow 0$
$P_{tx}^{max} \leftarrow \min\{P^{max}, \max\{P^{min}, P_{tx}^{est}\}\}$, where $P_{tx}^{est} \leftarrow \frac{T_{cs}}{I_{TX}} \cdot P^{min}$.
$SINR_{rx}^{max} \leftarrow \frac{P_{tx}^{max}/R^{\theta}}{I_{RX}}$
$k \leftarrow K$
while $r_{tx} = 0$, $r[k] > 0$, and $k > 0$ **do**
  if $SINR_{rx}^{max} \geq SINR_{r[k]}^{th}$ **then**
    $r_{tx} \leftarrow r[k]$
    $P_{tx} \leftarrow SINR_{r[k]}^{th} I_{RX} R^{\theta}$
  end if
  $k \leftarrow k - 1$
end while

Algorithm 2 Main Algorithm: *Standby Mode*

if $I_{TX} \leq T_{cs}$ **then**
  $N_s \leftarrow 0$ and $N_f \leftarrow 0$
  invoke *PRC*
  start transmission with P_{tx} and r_{tx}
end if

Algorithm 3 Main Algorithm: *Transmission Mode*

if *Transmission is success* **then**
  $N_f \leftarrow 0$ and $N_s \leftarrow N_s + 1$
  if $N_s \geq N_s^{th}$ **then**
    invoke PRC
    if $P_{tx} == 0$ **then**
      stop transmission
    else
      start transmission with P_{tx} *and* r_{tx}
    end if
  end if
else
  $N_s \leftarrow 0$ and $N_f \leftarrow N_f + 1$
  if $N_f \geq N_f^{th}$ **then**
    invoke PRC
    if $P_{tx} == 0$ **then**
      stop transmission
    else
      start transmission with P_{tx} *and* r_{tx}
    end if
  end if
end if

6. SIMULATION STUDY

In this section, we carry out a simulation study to evaluate the performance of *PRC* and compare it against three baseline algorithms: *Static*, *Dynamic Spatial Backoff (DSB)*, and *Greedy Power Control (GPC)*.

Algorithms used for evalaution:. *Static* uses a fixed transmit power and a fixed carrier sense threshold throughout the entire simulation run. In our simulation study, *Static* uses the same carrier sense threshold as *PRC*, but sets the transmit power to the average of of P^{min} and P^{max} of *PRC*. As summarized in Section 2, *DSB* [3] dynamically adjusts, based on consecutive successful/failed transmissions, both the carrier sense threshold and the data rate. *GPC* is a hypothetical, centralized algorithm that assumes global SINR and rate information of all the receivers. Each node uses the highest possible power, subject to the constraint that transmission with this power level will not reduce the data rates sustained by concurrent transmissions.

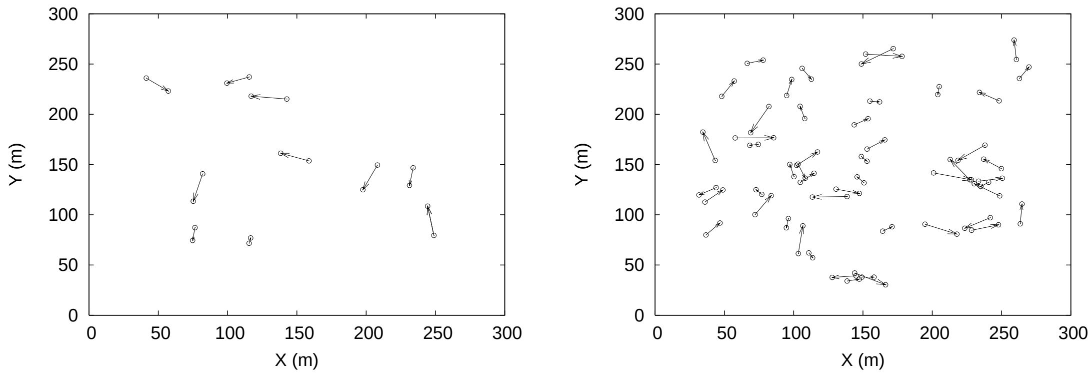
Table 2: Parameters used in the simulation study.

Parameter	Value	Parameter	Value
Propagation	Two-ray	Antenna height	1.5 m
Fixed CW Size	32 slots	RTS/CTS	Disabled
Thermal Noise	-95 dBm	RX Threshold	-64.38 dBm
P^{max}	-8.08 dBm	P^{min}	-12.16 dBm
P	-9.66 dBm	T_{cs}	-71.58 dBm

Simulation setup:. We have implemented *PRC* in ns-2 (Ver.2.28). In particular, we have modified ns-2 such that 1) the interference perceived at a receiver is the collective aggregate interference from all the concurrent transmissions, and 2) each node uses physical carrier sense to determine if the medium is free. We also incorporate the eight discrete data rates (Table 1) that are defined in the physical layer specification of IEEE 802.11a.

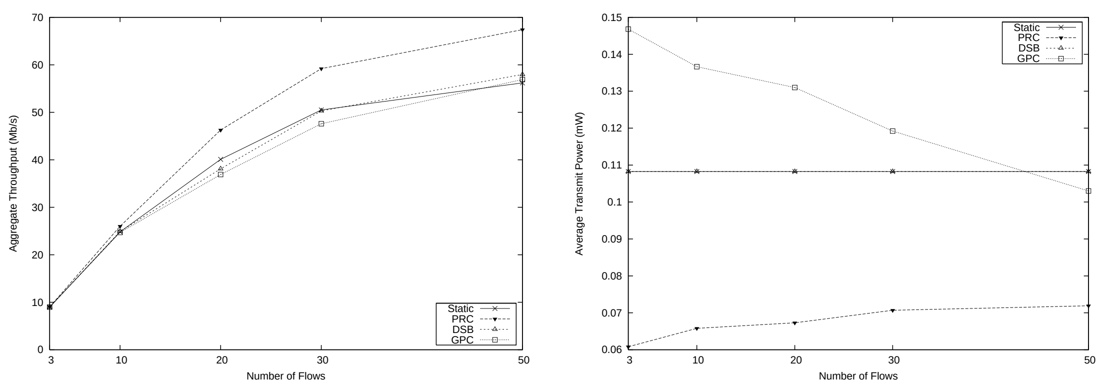
The parameter values used in the simulation study are given in Table 2. Note that P^{max} and P^{min} are the maximum and minimum transmission power used in *PRC*, and $\Delta_P = -20$ dBm is the the minimum unit of power change in *PRC*. For *PRC*, we set N_s^{th} and N_f^{th} to 10 and 5, respectively. *Static* and *DSB* uses the transmit power $P = \frac{P^{max} + P^{min}}{2}$ (which corresponds to the maximum transmission range of 35 meters). All the algorithms except *DSB* uses the same carrier sense threshold T_{cs}. The carrier sense thresholds set for different transmissions rates under *DSB* are obtained from [3] and given in Table 3.

In the simulation study, a total of 3, 10, 20, 30, and 50 transmitter-receiver pairs are randomly generated in a 300m × 300m area, and represent, respectively, sparsely, moderately, and densely populated networks. Figure 6 shows the network topology of 10 and 50 pairs used in the simulation.

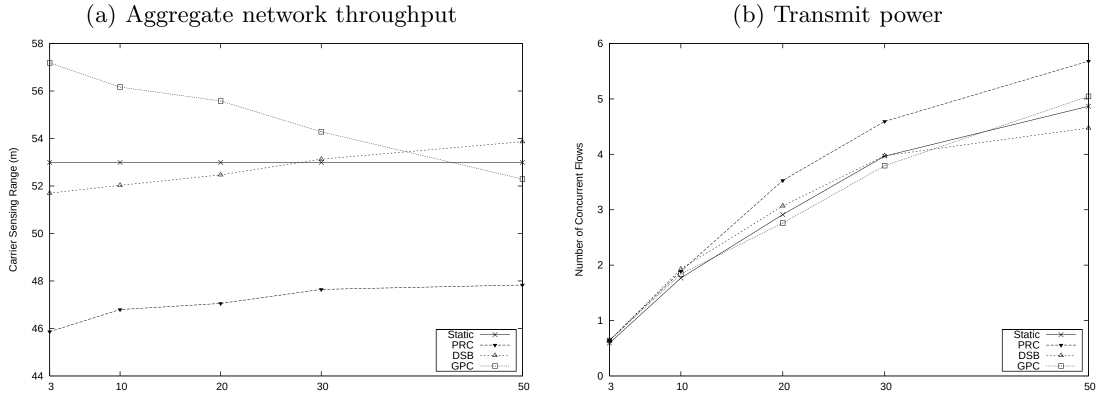


(a) 10 flows (b) 50 flows

Figure 6: Network topology of 10 and 50 transmitter-receiver pairs used in the simulation.



(a) Aggregate network throughput (b) Transmit power



(c) Carrier sense range (d) Number of concurrent transmissions

Figure 7: Aggregate network throughput, Transmit power, carrier sense range, and number of concurrent transmissions determined under the various algorithms, when the number of transmission pairs varies from 3 to 50.

Table 3: **Transmission rates and their corresponding carrier sense thresholds used in *DSB*.**

Rate	CS Threshold	Rate	CS Threshold
54 Mbps	-88.38 dBm	48 Mbps	-87.38 dBm
36 Mbps	-82.38 dBm	24 Mbps	-81.38 dBm
18 Mbps	-75.38 dBm	12 Mbps	-73.38 dBm
9 Mbps	-72.38 dBm	6 Mbps	-70.38 dBm

Simulation results:. Figure 7 (a) shows the aggregate network throughput achieved under various algorithms over 5 random topologies. In the relatively sparse network represented by 3 transmission pairs, all the algorithms achieve almost the same performance. In this case, the difference in the carrier sense range D under each algorithm is the largest (Figure 7 (c)), but the spatial reuse (represented by the number of concurrent transmissions) under all the algorithms are almost the same (Figure 7 (d)). This indicates that the carrier sense range D does not impact the aggregate throughput significantly. Rather the data rate attained by each transmission pair is the dominant factor. Because the transmitters are far apart from each other, they do not introduce significant interference to each other. As a result, high data rates can be easily sustained by each transmission pair. Moreover, since the interference level is low, the transmit power needs not be particularly high in order to attain such high data rates. *PRC* achieves the same throughput performance with the smallest transmit power (Figure 7 (b)). This implies *PRC* automatically detects the cases where high data rates can be substained *without* the use of a large transmit power, and operates in an economical manner.

As the network becomes more populated with more transmission pairs, the performance gap among the algorithms becomes more notable. *PRC* achieves the best performance when the number of transmission pairs varies from 10 to 50. This is because it enables the largest number of concurrent transmissions by using the smallest carrier sense range D. Moreover, it enables each transmitter to use an adequate power level that allows each receiver to sustain a high data rate while keeping the contribution to the interference level of other transmissions low. The benefit of power control becomes apparent when *PRC* is compared against *Static* (which uses a higher transmit power); the number of concurrent transmissions under *Static* is lower than that under *PRC*. This means a unnecessarily high transmit power can actually reduce the attainable data rate as well as the level of spatial reuse.

DSB uses a carrier sense range D that starts with a lower value but increases gradually with the population of network as shown in Figure 7 (c). Using the same transmit power as *Static* but with the smaller carrier sense range D in the rage of 3 to 20 flows, *DSB* introduces higher interference levels. As a results, *DSB* achieves higher spatial reuse (Figure 7 (d)). On the other hand, in the topology with 30 and 50 flows its carrier sensing range becomes larger than that of *Static*, and its discrepancy gets larger as the number of flows increases. This is because higher interference level incurred by larger number of flows reduces the carrier threshold level of *DSB* in order to secure successful transmissions. As a results, *DSB* achieves the lowest level of spatial reuse, but this consequently induces the highest transmission rate, leading to the second best performance at 50 flows as shown in Figure 7 (a).

As compared with *DSB*, even though *PRC* uses a smaller carrier sense range D, the fact that it uses a lower transmit power leads to less interference, and enables more concurrent transmissions with each sustaining a high data rate. This accounts for the better throughput performance achieved by *PRC*. An important observation is that for *DSB* the optimal value of T_{cs} for each transmission rate should be adjusted based on the network density and traffic distribution. As the node distribution in the vicinity of each transmitter may vary significantly, each node needs to properly tune its T_{cs} value for each data rate with respect to the node and traffic distribution. This may require the availability of non-local information.

In spite of the fact that *GPC* uses global information, as shown in Figure 7 (a), *GPC* gives the worst performance up to with 30 flows. Main reason for this is the transmit power level that it uses; in the network with 3 to 30 flows it uses the highest transmit power level as shown in Figure 7 (b). The high power level leads to the increase in the carrier sense range D and subsequently the decrease in spatial reuse. As the network becomes more populated, however, its maximum available power level becomes reduced. Although this leads to smaller carrier sensing range and lower transmission rate, higher level of spatial reuse offsets that and results in higher throughput performance than that of *Static* in the case of dense network represented by 50 flows.

7. CONCLUSIONS

In this paper, we have investigated the impact of spatial reuse on the network capacity. As there are two control knobs in the PHY/MAC layers to determine the level of spatial reuse: the transmit power P_{tx} and the carrier sense threshold T_{cs}, we study their relation by deriving the network capacity as a function of the two parameters. Another important factor that is taken into account in deriving the network capacity is the data rate that can be sustained given the SINR (which is itself a function of P_{tx} and T_{cs}). We show that (i) in the case that the achievable channel rate follows the Shannon capacity, spatial reuse depends only on the ratio of the transmit power to the carrier sense threshold. This implies that to improve the network capacity one can tune one parameter, while fixing the other at an appropriate value. (ii) In the case that only a set of discrete data rates are available, tuning the transmit power offers several advantages that tuning the carrier sense threshold cannot, provided that there is a sufficient number of power levels available.

Based on the above findings, we then propose a localized power and rate control (PRC) algorithm that enables each node to adjust its transmit power and data rate dynamically based on its signal interference level. From the interference level perceived at a transmitter, the transmitter determines its transmit power so that it can sustain the highest possible data rate, while keeping the adverse interference effect on the other neighboring concurrent transmissions minimal. Simulation results show that *PRC* achieves up to 22% improvement in the aggregate network throughput as compared to the Dynamic Spatial Backkoff (DSB) algorithm [3]. The better performance results from the fact that *PRC* uses a lower transmit power, which in turn induces low interference and enables better spatial reuse and achievable data rates.

8. ACKNOWLEDGMENTS

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