# 國立交通大學

電機學院通訊與網路科技產業研發碩士班

**碩士論文**

# 多通道多介面無線隨意網路之漸層式傳輸功率控制協定

# Gradational Power Control in Multi-channel Multi-radio Wireless Ad Hoc Networks

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**中華民國九十七年九月**

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## 摘　　要

在傳輸媒介共享的無線網路研究中，提出許多的傳輸功率控制協定來增加多重傳輸的數量以及減少干擾的影響，在本篇論文中，我們不嘗試提出一個新的傳輸功率控制協定，而是研究在每個通道都配置一個無線電傳輸設備的多通道無線網路環境中如何應用傳輸功率控制協定，而在多重跳躍通訊環境，單一無線電傳輸設備的傳輸端降低傳輸功率將會導致較低的網路連結率以及較長的傳輸路徑，另一方面，較低的傳輸功率能容納更多的傳輸端進行傳輸，因此，同時考慮傳輸路徑長度及傳輸媒介利用率這兩個參數來增加無線網路容量顯的更為重要，由於此動機，我們提出了一個可以應用在無線電傳輸介面並且獲得多重連結密度的傳輸功率控制協定，使得一個多重的網路拓樸擁有漸層式連結度在多個無干擾的通道中，稱之為漸層式傳輸功率控制協定（GradPC）。

在我們提出的漸層式傳輸功率控制協定（GradPC），基本通道被指定預設傳輸功率（無功率控制協定），而在其他非基本通道中，我們採用鄰近節點傳輸功率控制的方法來實現漸層連結密度，在漸層式傳輸功率控制協定（GradPC）配置所有無線電傳輸介面後，我們的協定執行以下兩個階段：(i）一個變異 DSR 在基本通道尋找多重跳躍節點的路徑，(ii)當路徑確定後，無線電傳輸介面依選擇程序來分配合適之通道，由於漸層式傳輸功率控制協定（GradPC）同時考慮路徑長度和傳輸媒介利用率因素，因此模擬結果顯示了我們所提出的漸層式傳輸功率控制協定（GradPC）的確優於其他功率控制協定。

# Gradational Power Control in Multi-channel Multi-radio Wireless Ad Hoc Networks

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## ABSTRACT

Various power control techniques have been proposed to boost aggregate network throughput by reducing the interference impact and encouraging more concurrent transmissions in medium-shared wireless systems. In this paper, we do not intend to devise new power control mechanisms. Rather, we investigate an interesting problem of how to apply power control techniques in a multi-channel networking environment, where every wireless node is equipped with multiple radio transceivers, each statically binding to a dedicated channel. For a single radio transceiver, more reduction on transmit power generally results in lower network connectivity, leading to a longer route (if path exists) for multi-hop communication (bad for end-to-end throughput). On the other hand, small transmit power helps accommodate more concurrent transmitters (good for aggregate throughput). For wireless ad hoc networks with multi-hop communication as the major behavior, how to take both route length and medium utilization into consideration to improve system capacity is thus important. Motivated by this, we propose to apply power control with different connectivity degrees on radio interfaces. Imagine several superposed network topologies having gradational connectivity levels over multiple non-interfering channels, hence the name, gradational power control (abbreviated as GradPC), is given. In our proposed GradPC protocol, a base channel is designated to use default transmit power (no power control on this radio). For other non-base radios, we adopt neighbor-based power control mechanisms to tailor the connectivity degree for each radio channel. After GradPC has successfully configured transmit power for all radios, our other corresponding protocols run in the following two phases: (i) a variant DSR is performed over the base channel to discover a multi-hop route, and (ii) once the route is ready, a radio selection procedure is activated to judiciously schedule the next link-layer packet sent over an appropriate channel. Simulation results demonstrate that the proposed GradPC along with its corresponding protocols outperform strategies with no power control and the same connected topology, by imposing gradational power levels on radios to balance the requirements for short route and high medium utilization.

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誌於 2008.09 新竹 交大

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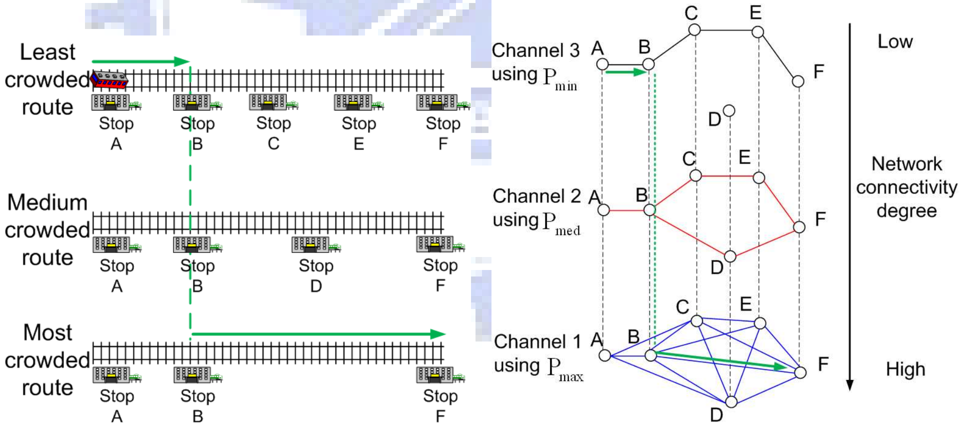
# Chapter 1

# Introduction

Researchers in the wireless networking community have been working diligently to expand observable system throughput for bandwidth-hungry applications. In [9], the authors analyze the capacity limitations of wireless networks from the perspective of information theory. Two types of networks are studied: arbitrary and random networks. Their analysis concludes that (1) the capacity (measured by the number of bits transmitted for unit distance in unit time) of an arbitrary network is of order $\Theta(\sqrt{n})$, where $n$ is the node density, while (2) the random network has a capacity of $\Theta(\sqrt{\frac{n}{\log n}})$. Based on the results, however, authors in [13] discover the capacity of a practical wireless 802.11 ad hoc network is remarkably below the theoretical bound. They observe that, without an optimal communication schedule, the 802.11 MAC throughput falls significantly short of the optimal capacity, due to either mis-interpreting the link idleness or generating too much local collision. An optimal communication schedule, if not impossible, is difficult to carry out especially in distributed ad hoc networks where stations operate independently without central coordination. While cross-layer interaction is essential, some research works investigate other capacity-controlling parameters. One such alternative is power control. In the literature, a number of power control techniques have been proposed [3, 8, 10, 14, 16–19, 21, 22]. power control directly affects the network connected topology (indirectly influencing the communication paths/schedules), and is generally interpreted as a means of alleviating interference impact because of reduced node degree (number of neighbors connected). In contrast to the previous argument, authors in [5] define a new notion of interference as the number of nodes being affected by communication over a certain link. Based on this new definition, they prove that *low node degree does not necessarily translate to low interference.* Two minimum spanning tree (MST) algorithms are thus proposed to produce interference-optimal topologies. However, in a later work [2] considering multi-hop communications, the authors oppose the MST-based topology constructions and prove that those "interference-optimal" topologies can perform badly form the viewpoint of multi-hop interference. We also observe, from our experiments (reported in Section 3), that power control surprisingly does not bring performance benefit for multi-hop traffic (actually performance hurt by power control compared to the case using default transmit power), partially due to the complicate multi-hop interference and partially the longer route resulted from power control. In this paper, we do not intend to propose new power control techniques. Instead, we investigate how to effectively apply a neighbor-based power control protocol in a multi-channel network to improve the multi-hop throughput.

Another capacity-controlling parameter is the wireless channel. Utilizing multiple non-overlapping radio channels is such an approach to improving system throughput by providing extra flowing pipes for communication packets without mutually interfering. The capacity benefit of equipping every wireless station with multiple radio interfaces, which operate over separate non-interfering channels, is understandable, at the expense of hardware cost. As the price of radio modules steadily goes down, the cost of installing multiple wireless network cards (NICs) has been considered feasible. In [12], the authors suggest each node equipped with two radio transceivers, one is fixed on a certain channel, while the other is made switchable between the rest of channels. According to the authors, the strategies of binding network interfaces to radio channels can be classified as static, dynamic, and hybrid. Static binding assigns each interface to a channel permanently or for a long time period, whereas dynamic binding allows an interface to frequently switch channels from one to another. Hybrid binding is realized by applying static binding for some interfaces and dynamic binding for other interfaces. Frequent switching from channel to channel at a radio interface may result in undesirable network partition and the multi-channel hidden-terminal problem. The multi-channel hidden-terminal problem leads to unnecessary collisions, because the channel status cannot be monitored continuously and precisely due to channel switching. In this paper, we adopt the static binding for all radio interfaces.

Instead of studying the above power and channel factors separately, we consider the pros and cons of power control mechanisms, and propose a gradational power controlling (GradPC) method over multiple non-overlapping wireless radio channels (channel diversity). The concept of GradPC is illustrated in Fig. 1.1. Suppose an imaginary railway system (as shown in Fig. 1.1(a)) has three passenger routes (all with the same train speed). The least crowded route has the shortest waiting queue, but with the most stops to drop and reload passengers. On the other extreme, the most crowded route has the longest waiting queue, but wasting the least time to stop for passengers get-on/off. Assume that the route-transfer time within the same stop is negligible. In order for a passenger to plan a trip from Stop A to Stop F, taking the least crowded train at Stop A (to avoid long waiting queue), and then making a transfer at Stop B (transfer time assumed to be very small) is perhaps the fastest path. In comparison to our multi-channel networking environment, the three train routes with different congestion levels can be interpreted as three network topologies produced by different degrees of power control. Different power control degrees result in heterogeneous connectivity status (as shown in Fig. 1.1(b)). By using the minimal transmit power $P_{min}$, Channel 3 is the least congested (shortest in-line queue of the railway example), but with longer route. On the other hand, Channel 1 is the most congested (longest in-line queue), but route can be much shorter. Also assume the channel switching delay within the same node is insignificant. Consequently, sending packets over Channel 3, and then making a channel switching at node B is likely to be the most efficient routing path under such multi-channel environment. In reality, the train transfer time in the railway system may not possibly be made zero, while in wireless networks, the channel switching delay can be made negligible by equipping each node with multiple radio interfaces all binding to respective channels. Motivated by this concept, in this paper, we propose to apply power control with different connectivity degrees on radio interfaces. Imagine several superposed network topologies having gradational connectivity levels over multiple non-interfering channels, hence the name, gradational power control (abbreviated as GradPC), is given.



(a) shows perhaps the fastest travel path by our imaginary railway system.

(b) plots possibly the most efficient packet route over the multi-channel network.

Figure 1.1: Illustration of GradPC concept.

The rest of this paper is organized as follow. Section 2 reviews existing power control techniques and summarizes our contributions. Section 3 first theoretically investigates the impact of power control on a single-channel single-radio grid network capacity. For single-hop communications, due to the improved spatial diversity, system throughput after exercising power control is way better than that using default transmit power. However, for multi-hop traffic, the system performance is reversed, resulting in a much better throughput when using the default transmit power (no power control). This anomalous phenomenon implies that other parameters should also be factored in besides the spatial diversity, in order to improve the system throughput of multi-hop traffic. This motivates us to propose the GradPC and its corresponding protocols to address the multi-hop issues in Section 4. We observe that our GradPC works out the most throughput potential of a multi-channel multi-radio grid network in terms of multi-hop performance. In Section 5, we apply the GradPC protocol suite in a multi-channel multi-radio random node topology, so as to further corroborate the effectiveness of our proposed methodology. Finally, Section 6 draws our conclusion and map out the future work.

# Chapter 2

# Related Work

## 2.1 Power Control Techniques

Traditional power control techniques aim to balance between energy conservation and network connectivity [3, 8, 10, 14, 16–19, 21, 22]. In this paper, we are more concerned with network connectivity while keeping the interference impact low. We adopt the power control mechanism proposed in [22] (the N-base protocol). According to the authors, [22] was motivated by the classic work in [8] (Theorem VII.3 in [4]). N-base is a neighbor-based power control protocol. The main contributions of [22] include theoretically deriving the number of neighbors that each node should be connected to for the good connectivity of a multi-hop network. The authors conclude that in a network with $n$ randomly deployed nodes, $\Theta(\log n)$ neighbors should be connected (here log indicates natural logarithm with base $e$), in contrast to the magic number of six. When neighbor number is less than $0.074 \log n$, they prove that the network is asymptotically disconnected with probability one as $n$ increases. When neighbor number is greater than $5.1774 \log n$, then the network is asymptotically connected with probability approaching one as $n$ grows. The critical constant before $\log n$ remains open and unresolved. In this paper, we adopt this N-base protocol as our power control mechanism. In particular, to provide power gradations, we tune the respective radio power so as to connect to less and less neighbors gradually. In our GradPC policy, we use default transmit power over the base channel (without power control). For other non-base channels, we impose gradational power reductions to produce different neighbor connectivity levels based on the N-base protocol (detailed algorithm presented in Section 4.1).

Another perspective taken by power control recently is to improve the spatial diversity. Spatial diversity can be comprehended as medium utilization, and achieved by adjusting power sensitivity [1, 7, 11, 15, 23]. Spatial diversity is generally measured by the spatial reuse factor, which can be affected by tuning either the transmit power level or tuning carrier sense threshold. Higher spatial reuse factor means more concurrent transmitters and usually better system throughput. The objective of power control techniques in this category is to open up more system capacity, while energy saving is only a side benefit.

A comparison report on various power control mechanisms can be found in [20].

## 2.2 Our Contribution

Previous works [17, 21] on multi-channel power control studies hold major different objectives and methodologies from ours:

**(1)** The main purpose of [17, 21] is to propose a power control technique with the assistance of one extra channel for control signaling. On the other hand, we do not intend to devise a new power control mechanism. Rather, we attempt to jointly exploit both the power parameter and channel diversity, in order to further improve the multi-hop performance in a wireless ad hoc network.

**(2)** A dedicated control channel is used by [17, 21] to negotiate an appropriate power level to use via RTS/CTS handshaking on a per-packet basis. On the other hand, all channels are data channels in our work and no power negotiation (RTS/CTS overhead) is necessary, since we adopt a neighbor-based power control protocol to statically configure the power level for each radio.

In our proposed GradPC protocol, a base channel is designated to use default transmit power (no power control on this radio). For non-base radios, we adopt the aforementioned N-base power control mechanisms to tailor the connectivity degree for each radio channel. After GradPC has successfully configured transmit power for all radios, our other corresponding protocols run in the following two phases: (i) a variant DSR is performed over the base channel to discover a multi-hop route, and (ii) once the route is ready, a radio selection procedure is activated to judiciously schedule the next link-layer packet sent over an appropriate channel. Simulation results demonstrate that the proposed GradPC along with its corresponding protocols yield better multi-hop performance than strategies with no power control and the same connected topology, by imposing gradational power levels on radios to balance the requirements for short route and high spatial diversity.

# Chapter 3

# Single-channel Single-radio Grid Network

In this section, we begin our discussion by theoretically analyzing the impact of power control on system throughput from the perspective of Shannon's capacity law and medium reuse factor in a single-channel single-radio grid network. Since we adopt the N-base protocol as our power control strategy [22], our analysis is closely related to the property of N-base protocol. As we mentioned in Section 2.1, the theoretic base is: the number of neighbors that should be connected for certain network connectivity is of order $\Theta(\log n)$, where $n$ is the number of neighbor nodes covered by using the default transmit power before N-base is performed. Based on this analytic base, here we assume the critical constant before the logarithm to be one. Specifically, suppose the number of connected neighbors (using the default transmit power) is $n$, after exercising the N-base protocol, the radio transmit power is engineered so as to connect to only $\log n$ neighbors.

## 3.1 Network Model

We study a single-channel grid network where $n$ nodes are uniformly distributed in an area $A$ (hence the node density $\lambda = \frac{n}{A}$). Suppose all nodes use the same default transmit power $P_{tr}$. Assume only large-scale path loss is considered for radio signal propagation (with path loss exponent $\alpha$), the received power level $P_{rcv}$ at distance $d$ can be denoted as $P_{rcv}(d) = \frac{KG_tG_rP_{tr}}{d^\alpha}$, where $G_t$, $G_r$ are the antenna gains of transmitter and receiver respectively, and $K$ is an environmental constant. In general, we assume $K = G_t = G_r = 1$. Thus the received power level $P_{rcv}(d) = P_{tr} \cdot d^{-\alpha}$. When the default transmit power $P_{tr}$ is used, all $n$ nodes are connected neighbors. We call this a *single-cell* communication scenario, since only one communication link can be active in this cell. After the N-base power control protocol is performed, the number of neighbors connected by each node reduces to $\log n$, resulting in a *multi-cell* communication scenario. For the multi-cell communication scenario, several concurrent transmissions take place in multiple communication cells. In the following analysis, we first look at the link capacity $C$ of a communication cell using default transmit power $P_{tr}$, and link capacity $C_p$ of a communication cell after applying the N-base protocol. Then we extend the results to derive system capacity by considering all communication cells.

We denote the system capacity with no power control as $C^m$, whereas system capacity after applying the N-base protocol as $C_p^m$. Note that $C = C^m$ since there is only one communication cell in the case of no power control.

## 3.2 Impact of Power Control on Network Capacity

### 3.2.1 Shannon's Capacity Law

In order to analyze the capacity of a single communication cell, we utilize Shannon's capacity law to derive the link throughput. According to Shannon's capacity law, the channel capacity can be modeled as

$$Capacity = B \log_2(1 + SINR), \tag{3.1}$$

where $B$ is the channel bandwidth (in Hertz), and $SINR$ is the ratio of received signal power divided by sum of interference $P_I$ and noise power $\eta$. That is,

$$SINR = \frac{P_t \cdot d^{-\alpha}}{P_I + \eta}. \tag{3.2}$$

For the case with no power control, $P_t = P_{tr}$ (recall that $P_{tr}$ is the default transmit power). After applying the N-base protocol to reduce the number of connected neighbors to $\log n$, we have the reduced transmit power

$$P_{trp} = P_{tr} \times \left( \sqrt{\frac{\log n}{n}} \right)^{\alpha}. \tag{3.3}$$

As to the interference power, we approximate the derivation based on the methodology proposed by [15]. According to the authors, $P_I$ should consider accumulated interference power from stations outside the carrier sense range $d_{cs}$ and inside the radio propagation distance $d_{pg}$. Since $d_{cs}$ and $d_{pg}$ are determined by the carrier sense power threshold and signal sensitivity threshold respectively, the N-base protocol directly influences the two ranges given the two power thresholds remain the same. Consequently, the reduced carrier sense range $d_{csp}$ and radio propagation distance $d_{pgp}$ can be expressed as

$$d_{csp} = d_{cs} \times \sqrt{\frac{\log n}{n}}, \tag{3.4}$$

$$d_{pgp} = d_{pg} \times \sqrt{\frac{\log n}{n}}. \tag{3.5}$$

In addition, due to the back-off strategy to avoid collision in medium-shared networking system, generally stations have certain transmission attempt probability based on the contention mechanism. In other words, stations outside $d_{cs}$ (or $d_{csp}$) and inside $d_{pg}$ (or $d_{pgp}$) may or may not contribute to the interference power $P_I$. Suppose the IEEE 802.11 MAC is considered. Based on the derivations from [6], the transmission attempt probability $p_a$ can be approximated as $p_a \approx \frac{2}{CW+1}$, where $CW$ is the average contention window size as in 802.11 DCF. Now, the interference power caused by the case using default transmit power $P_{tr}$, denoted as $I$, can be expressed as

$$I = \frac{p_a \cdot (\lambda\pi d_{pg}^2 - \lambda\pi d_{cs}^2) \times P_{tr}}{\left(\frac{d_{pg} - d_{cs}}{2}\right)^{\alpha}}. \tag{3.6}$$

Similarly, we can derive the interference power $I_p$ produced after applying N-base protocol as

$$I_p = \frac{p_a \cdot (\lambda\pi d_{pgp}^2 - \lambda\pi d_{csp}^2) \times P_{trp}}{\left(\frac{d_{pgp} - d_{csp}}{2}\right)^{\alpha}}. \tag{3.7}$$

By letting $P_I = I$ and $P_t = P_{tr}$ in Eq. 3.2, we obtain the link capacity $C$ (Eq. 3.1) for the communication cell without power control. Likewise, by letting $P_I = I_p$ and $P_t = P_{trp}$ in Eq. 3.2, we can derive the link capacity $C_p$ for a communication cell resulted from performing the N-base protocol.

Assume $n$ nodes are uniformly placed in a 220 × 220 square meters area. Suppose channel bandwidth $B = 22M$ Hertz (802.11b channel bandwidth), and path loss exponent $\alpha = 2$. The default transmit power $P_{tr}$, carrier sense threshold, receiving threshold, and noise power $\eta$ are set as 20dBm, -99dBm, -95dBm, and -101dBm respectively. Only single-hop traffic flows are considered, and communication takes place between neighboring nodes (hence the distance $d$ can be inferred). Fig. 3.1 illustrates the impact of N-base power control protocol on interference and transmit power. Fig. 3.1(a) shows the interference power level before and after the power control. We observe that as $P_I$ is reduced ($I_p < I$) by power control, $P_t$ is also deducted ($P_{trp} < P_{tr}$). Fig. 3.1(b) shows that the numerator and denominator of $SINR$ (in Eq. 3.2) both decrease in the same manner (two curves merge to one), resulting $C = C_p$.

### 3.2.2 Spatial Reuse Factor

Despite the link capacity in a communication cell turns out to be immune to protocol control ($C = C_p$), the aggregate system capacity can benefit from multiple concurrent communication cells enabled by power control. Those multiple communication cells generally represent the spatial reuse factor in a medium-shared network. In other words, spatial reuse factor can be measured by the number of maximum concurrent transmissions. Recall the total area is $A$. Define the "consumed area" $A_s$ by each transmitter for the case of no power control, $A_s$ ranges from $\frac{\sqrt{3}}{2}d_{cs}^2$ to $\frac{3\sqrt{3}}{2}d_{cs}^2$ [23]. Similarly, for the case of applying N-base protocol, consumed area $A_{sp}$ ranges from $\frac{\sqrt{3}}{2}d_{csp}^2$ to $\frac{3\sqrt{3}}{2}d_{csp}^2$. Now, for the same network node distribution, we have $A_s = \beta \cdot d_{cs}^2$ and $A_{sp} = \beta \cdot d_{csp}^2$, where $\beta$ is a network-dependent constant ($\frac{\sqrt{3}}{2} \leq \beta \leq \frac{3\sqrt{3}}{2}$). Define the spatial reuse factor $u$, we have

$$u = \frac{A/A_{sp}}{A/A_s} = \frac{A_s}{A_{sp}} = \frac{n}{\log n}. \tag{3.8}$$

Table 3.1 summarizes notations used in Section 3.2.1 and Section 3.2.2.

Table 3.1: Summary of Notations

| Notation | Description |
|---|---|
| $\lambda$ | Node density of the grid topology |
| $\alpha$ | Path loss exponent |
| $d$ | Communication distance between transmitter and receiver |
| $p_a$ | Transmission attempt probability |
| $P_{tr}$ | Default transmit power |
| $P_{trp}$ | Reduced transmit power after applying the N-base power control |
| $d_{cs}$ | Default carrier sense range |
| $d_{csp}$ | Carrier sensing range after applying the N-base power control |
| $d_{pg}$ | Default radio propagation distance |
| $d_{pgp}$ | Radio propagation distance after applying the N-base power control |
| $n$ | Estimated number of neighbors using default transmit power $P_{tr}$ |
| $u$ | Spatial reuse factor |

### 3.2.3 Aggregate Network Throughput

To obtain the aggregate capacity, we simply add up link capacities of all communication cells in the network. Thus the aggregate throughput for the case of no power control $C^m = C$, since there is only one communication cell. On the other hand, the aggregate throughput for the case of applying N-base protocol $C_p^m = u \cdot C_p$, because multiple communication cells exist. As a result, we obtain the aggregate capacity ratio $\frac{C_p^m}{C^m}$ as

$$\frac{{C_p}^m}{C^m} = \frac{C_p}{C} \cdot u = \frac{n}{\log n}. \tag{3.9}$$

Fig. 3.2 illustrates the impact of power control on aggregate network capacity. In the following subsection, we run experiments in the ns-2 simulator to validate the analytic results presented in this section, and identify the harmful effect caused by power control for multi-hop traffic.

## 3.3 Performance Evaluation

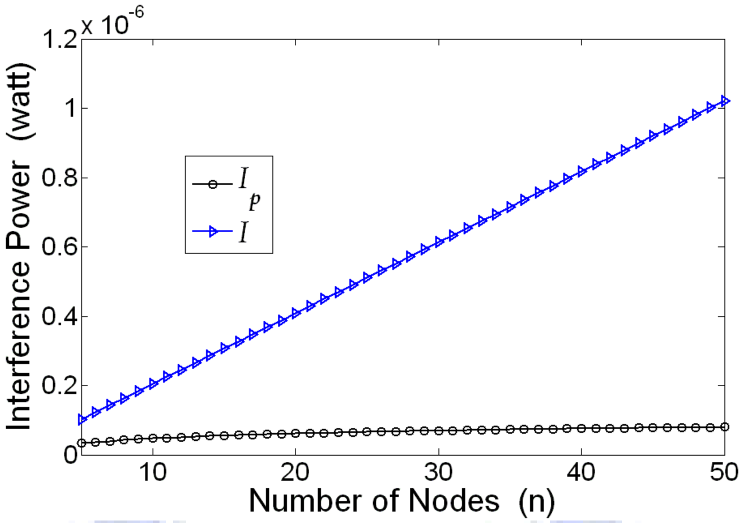
Table 3.2 lists the parameters we use in the ns-2 simulations. We use the IEEE 802.11b wireless module with link rate of 11M bps. RTS/CTS handshaking is disabled. All nodes are uniformly deployed in an area of $220 \times 220$ sq. meters. As shown in Fig. 3.3, both single-hop and multi-hop traffic are generated for grid networks of 9, 25, and 49 nodes. To avoid the corner effect which may bias the results, we actually generate more nodes and traffic flows so that the corner nodes can have the same surroundings as the central nodes. Simulation statistics are obtained from the central 9, 25, and 49 nodes of the network. In Fig. 3.4(a), **Default** indicates the method with no power control (using default transmit power), whereas **N-base** means the method that applies N-base protocol. We observe that for single-hop traffic (Fig. 3.3(a)), N-base performs much better especially in dense networks. This is because more spatial diversity is achieved by N-base. Recall that $n$ is the number of connected neighbors when using the default transmit power. According to the derivation in Eq. 3.9, the ratio of $\frac{n}{\log n}$ determines the scale that system throughput can be improved by power control. In our experiments, $n = 8, 24,$

and 44 for the 9-, 25-, and 49-node grid topologies. Apparently the denominator $\log n$ of Eq. 3.9 increases much slower than the numerator $n$ as $n$ grows. Thus the ratio is expected to increase drastically as network becomes dense, which explains Fig. 3.4(a). Note that in our grid examples, due to the equal distance between four closest neighbors, in our simulations, the number of connected neighbors after N-base power control is always four. The reason is the logarithms of 9, 25, and 44 are all less than four, and in grid topology, a node will connect to zero neighbor if power is reduced to connect to less than four neighbors (i.e., $\log n = 4$ for all three node densities). In order to validate our analytic model, we obtain the ratio of simulative system throughput with Default to that with N-base, and compare to the analytic ratio of $\frac{n}{\log n}$. The results in Fig. 3.4(b) shows that the analytic predictions are quite close to the simulative outcomes.

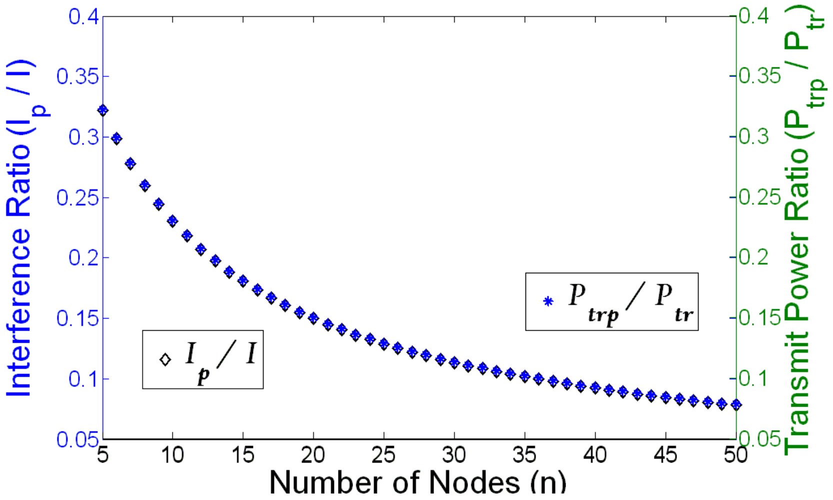
Table 3.2: Parameters used in NS-2 simulation

| **Two-Ray Ground Propagation Model** | |
|---|---|
| Antenna Gain = 1 | $CW_{min} = 32$<br>$CW_{max} = 1024$ |
| Default $P_{tr} = 20$dBm | Noise $= -101$dBm |
| CSThreshold $= -99$dBm | RXThreshold $= -95$dBm |
| CBR sending rate = 1Mbps | |
| Packet size = 1024 bytes | |

So far, power control seems to yield better system throughput by bringing more spatial diversity (enabling multiple concurrent communications). However, as shown in Fig. 3.5, the N-base method performs poorly for the multi-hop traffic in terms of system throughput. This erratic phenomenon suggests that the spatial diversity advantage of power control no longer dominates the performance for multi-hop traffic. In contrast, complicate inter-hop interference and lengthened packet route affect the multi-hop performance in a bad way. Motivated by this observation, we seek to balance the pros and cons of power control for multi-hop traffic with the assistance of using multiple wireless radio channels.



(a) shows the interference power before and after power control.



(b) illustrates the ratio of default interference (transmit) power divided by reduced interference (transmit) power.

Figure 3.1: Impact of power control on interference power and transmit power.

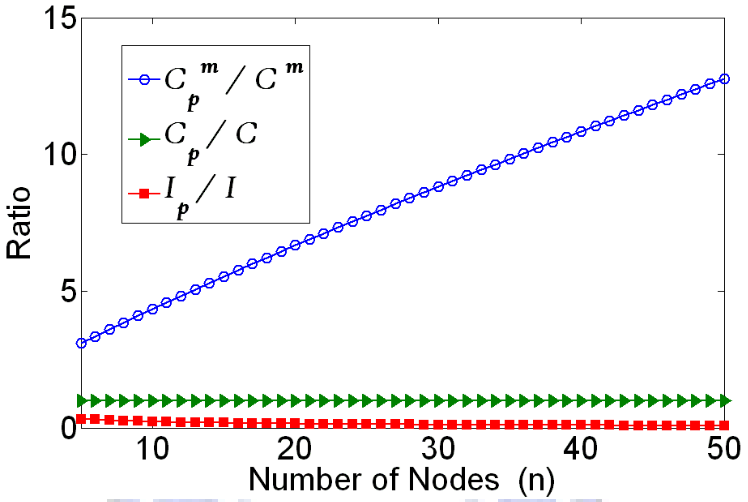
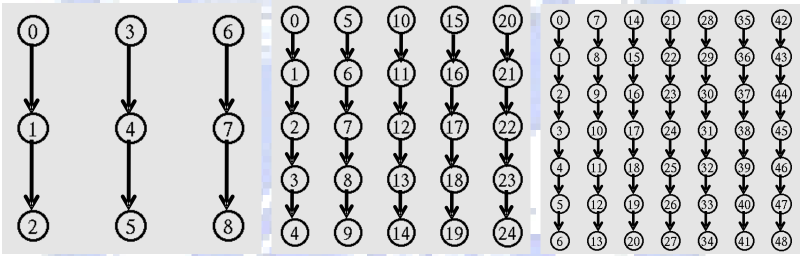
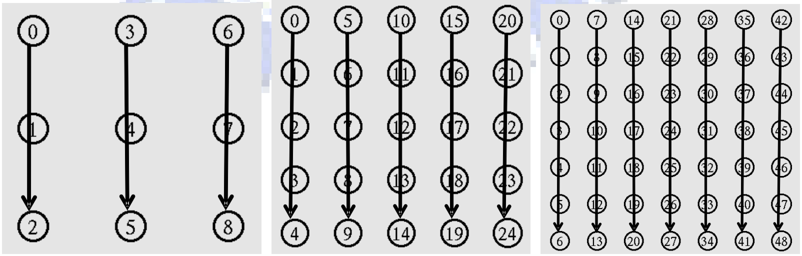


Figure 3.2: Impact of power control on network capacity.

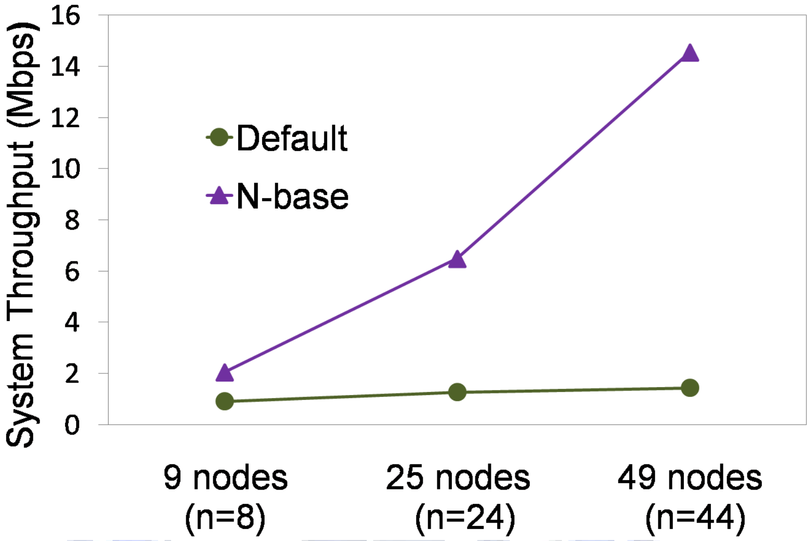


(a) Single-hop traffic

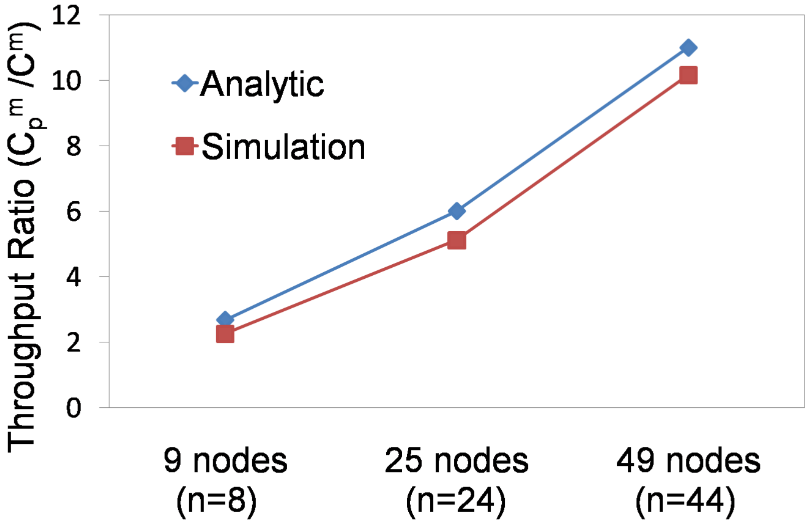


(b) Multi-hop traffic

Figure 3.3: The single-channel single-radio grid network with 9, 25, and 49 nodes respectively.



(a) Throughput



(b) Ratio of $\frac{C_p^m}{C^m}$

Figure 3.4: Single-hop traffic performance in a single-channel single-radio grid network.

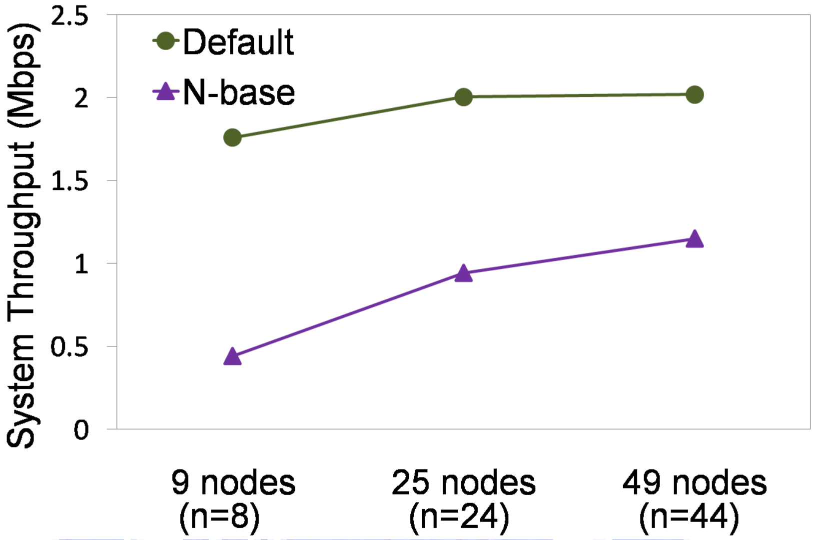


Figure 3.5: System throughput for multi-hop traffic in a single-channel single-radio grid network.

# Chapter 4

# Multi-channel Multi-radio Grid Network

In this section, we consider a grid network with $I$ radio interfaces at each node, running over $C$ non-interfering channels. Here $I \leq C$. In case $I < C$, a common subset (with size $I$) of $C$ channels will be selected so that every node uses the same channel set to configure channels for its $I$ radios. We are interested in improving the system performance with multi-hop communications. To this end, we first propose our GradPC framework in Section 4.1, and then report the performance results via simulations in Section 4.2.

## 4.1 Gradational Power Control Protocol (GradPC)

The design rationale behind the GradPC protocol is to impose power gradations on radios equipped at each node, so as to provide flexibility of bal-

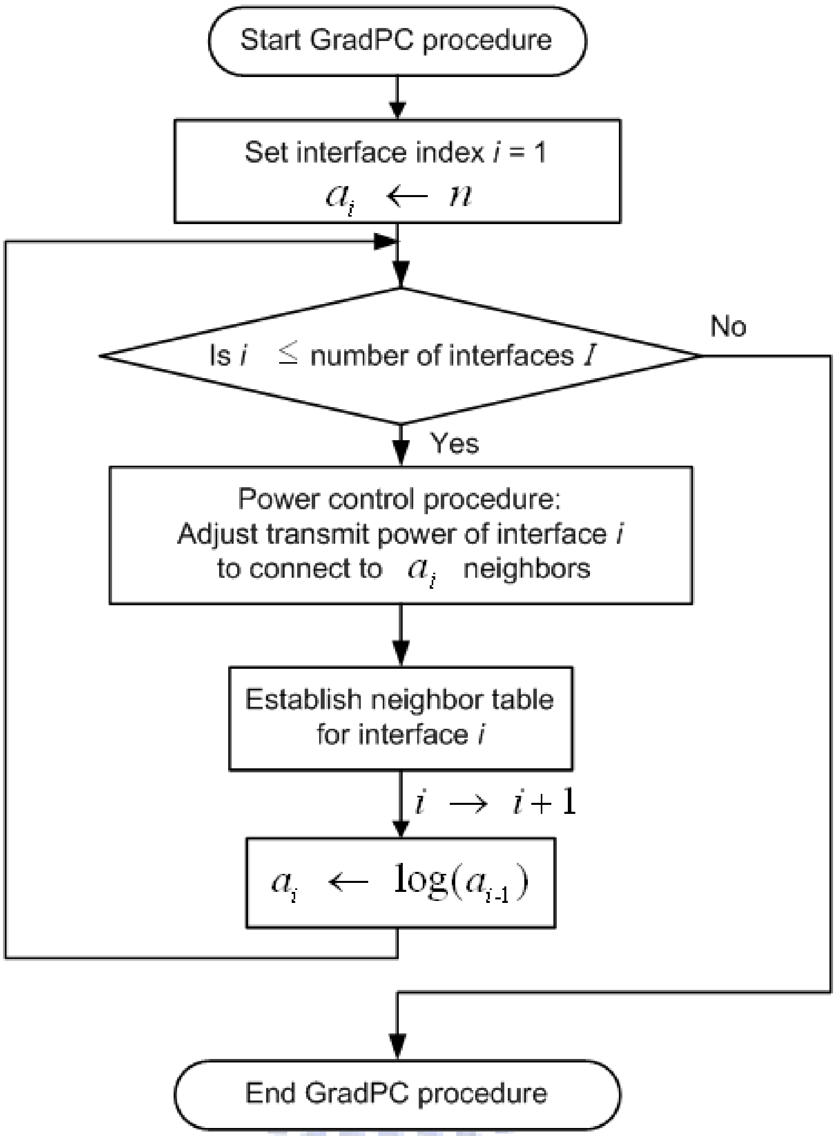


Figure 4.1: The GradPC procedure to impose power gradations on radios at each node.

ancing the contradicting factors, such as route length and spatial diversity, for multi-hop traffic performance. In the proposed GradPC framework, a base channel is designated to always use the default transmit power $P_{tr}$ (no power control on this radio). In this way, the route can be kept short, and network connectivity can be preserved despite performing power reductions on the other non-base radios. Define the neighbor table (set) established over base channel as $N_{base}$, and $n$ denotes the cardinality of set $N_{base}$ (size of neighbor nodes over base channel). Parameter $n$ can be easily obtained by implementing heart-beat message (e.g., HELLO) exchanging mechanisms at each node. Consequently, nodes can estimate their respective $n$ value by periodically exchanging HELLO messages over the base channel. In addition, the base channel is responsible for finding packet routes due to its high network connectivity. In the current GradPC framework, we adopt a variant of DSR routing mechanism, which always gathers three possible routes and then randomly chooses one. In contrast to favoring the shortest route in default DSR, the selected route in our GradPC protocol may not be the shortest. Generally speaking, the shortest route comes with longer traveling distance between hops. In order to support long transmitting distance, high transmit power should be used. As a result, we observe that in many cases, default transmit power is necessary to support the route discovered by default DSR over the base channel. On the other extreme, we may choose the longest route, which produces short traveling distance between hops. In this case, the required power level can be reduced, but the end-to-end throughput may suffer due to many unnecessary relays. The above observations motivate us to adapt the DSR protocol. Our objective is to determine a moderate route path which has mixed short and long hops. Such route provides us flexibility of scheduling different channels and power levels to be used between hops.

For non-base radios, our GradPC adopts the N-base protocol as the power control mechanism. Specifically, once $n$ is obtained from the base channel, the GradPC procedure reduces power levels gradationally so that the connectivity degrees for non-base channels become less and less. Fig. 4.1 illustrates the GradPC procedure. After GradPC procedure is done, the transmit power level $P_t^i$ that should be used by radio $i$ is obtained. Then each non-base radio should perform the heart-beat message exchanging function to establish the neighbor table (set) $N_i$ for radio interface $i$. Note that when tuning the power level for a non-base radio, we follow the ns-2 settings which divides power into ten levels ranging from 1mW to 100mW. That is, power is reduced by 10mW at a time until the number of connected neighbors satisfies the desirable number. Once the power levels have been determined for all radios, and route is ready, an interface scheduling procedure is performed to schedule the next packet to be sent over an appropriate channel (radio). Given a packet route, we consider both channel diversity between hops and spatial reuse factor resulted from power control. Generally, the radio interface with the lowest transmit power is preferred, suppose the next hop is reachable using this transmit power. In addition, to provide channel diversity between hops, we propose to circulate the channel assignment by avoiding the channel used by the previous hop. Define $Ch_{pre\_hop}$ as the channel ID used by the previous hop. Each node sets the initial channel ID to be considered as $f_I(Ch_{pre\_hop} - 1)$, where $f_I$ is a circulation function, so that the function value always takes on some integer between $[1, I]$. This mechanism does provide certain channel diversity between hops, but do not guarantee absolute diversity. Fig. 4.2 illustrates our interface scheduling policy in the GradPC framework. More detailed pseudo-codes are presented below to show the internal operations of the GradPC protocol.

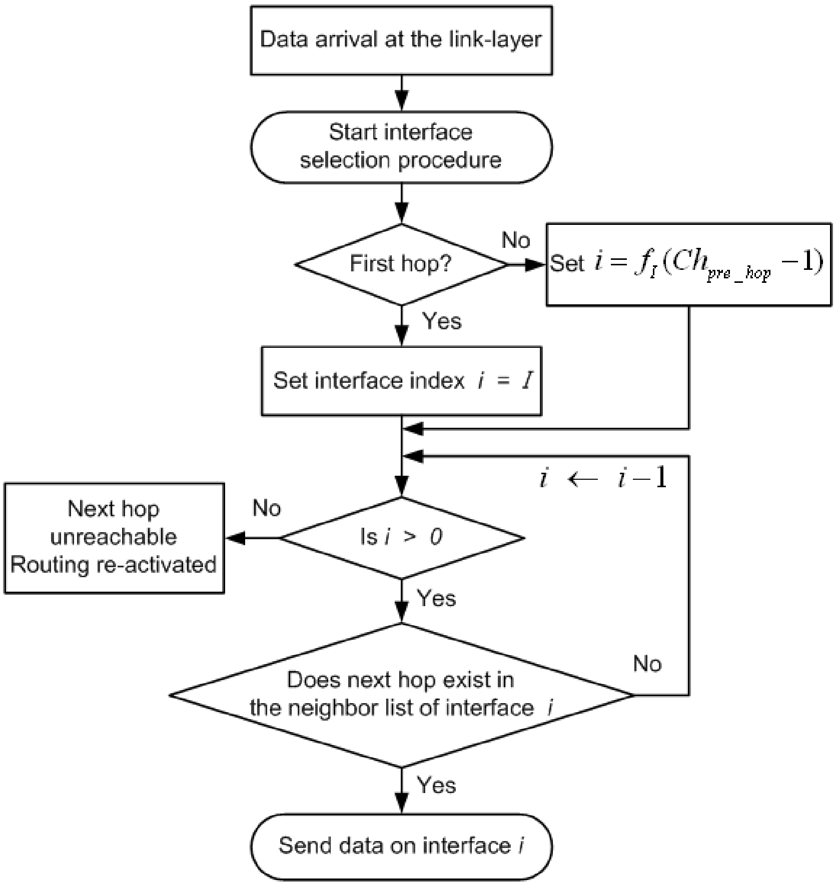


Figure 4.2: Interface scheduling policy after route is ready.

**Algorithm 1** Establish neighbor table using base channel: estimation of parameter $n$

```
$P_t \leftarrow P_{tr}$ // set default transmit power
$n \leftarrow 0$
Send message(HELLO) periodically over base channel using transmit power $P_t$
while (HELLO received) and (!Timeout) do
    Add node's ID to neighbor table $N_{base}$
    $n \leftarrow n + 1$
end while
```

**Algorithm 2** GradPC procedure: power adaptation policy for respective radio interface at each node

```
$I \leftarrow$ Number of interfaces
$i \leftarrow 1$ // interface index
$a_1 \leftarrow n$ // $n$ obtained from Algorithm 1
while $i \leq I$ do
    $P_t^i \leftarrow P(a_i)$ // power adjustment function for radio $i$ to connect to $a_i$ neighbors
    Establish neighbor table $N_i$
    if $a_i \geq e$ then
        $i = i + 1$
        $a_i \leftarrow \lceil log(a_{i-1}) \rceil$
    else
        $i = i + 1$
        $a_i \leftarrow a_{i-1}$
    end if
end while
```

## 4.2 Performance Evaluation

In this section, we extend the ns-2 code to support multi-channel multi-radio environment. We use the 3 non-overlapping channels (numbering as channel 1, 2, and 3) in IEEE 802.11b, and install 3 radio interfaces at each node. Channel 1 is designated as the base channel. The same ns-2 parameters

**Algorithm 3** Interface selection procedure: data will be sent over the selected radio

```
if First hop then
    $i \leftarrow I$ // initial interface index
else
    $i \leftarrow f_I(Ch_{pre\_hop} - 1)$
end if
while $i \geq 1$ do
    if Next hop found in $N_i$ then
        Data sent over radio $i$
    else
        $i = i - 1$
    end if
end while
// next hop unreachable
Re-discover route on base channel
```

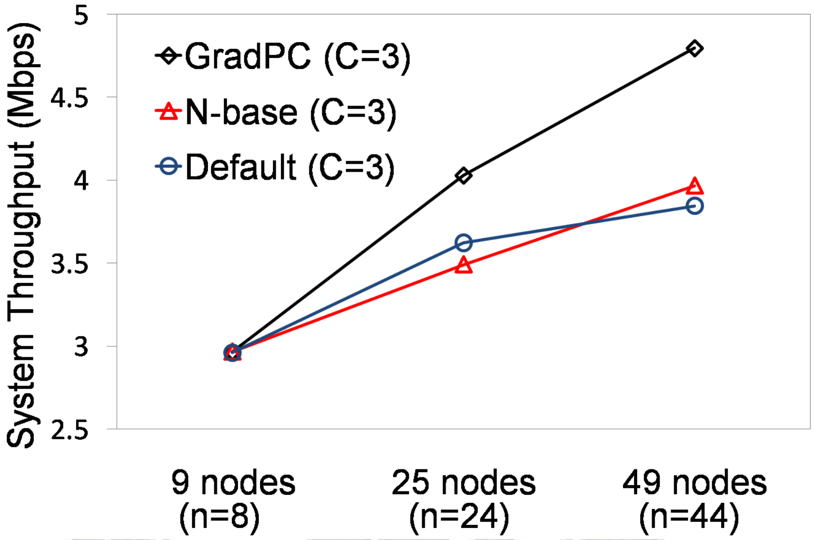
(Table 3.2) and network topologies (Fig. 3.3) are used in our simulations. We investigate the system throughput of multi-hop flows (Fig. 3.3(b)) for three approaches: GradPC, N-base, and Default. All three approaches use 3 non-overlapping channels and 3 radio interfaces at each node. **Default** indicates the method of using default transmit power for all three radios, whereas **N-base** denotes the approach of applying the same power level to connect to $\log n$ neighbors for all three radios. Since there is no interface scheduling mechanism specified for Default and N-base, in order not to take advantage of them in this regard, we implement the same interface scheduling algorithm (shown in Fig. 4.2) as GradPC in Default and N-base. For routing strategy, Default and N-base use the shortest routes found by DSR using their respective power levels, while GradPC use routes randomly chosen from the first three routes discovered by DSR (explained previously in Section 4.1).

Fig. 4.3(a) plots the system throughput of multi-hop traffic flows (generated as in Fig. 3.3(b)). With the assistance of channel diversity, the performance of Default and N-base is comparable, in contrast to the sharp performance degradation produced by N-base as previously shown in Fig. 3.5 when $C = 1$ (single-channel environment). From Fig. 4.3(a), we observe that our GradPC performs the best especially for dense networks. To get a better understanding of the impact on multi-hop traffic performance, we give another set of statistics in Fig. 4.3(b), which shows the system performance of a dense grid network (49 nodes) as the number of multi-hop flows increases. As we can see from this figure, when $C = 1$ (single-channel system), no power control is suggested in terms of better multi-hop traffic performance. When $C = 3$ (multi-hop environment), interestingly, N-base is not always worse than Default. For environments with very light and very heavy loads (2 and 7 flows), N-base even performs better than Default. We extrapolate from the results that both route length and medium utilization (spatial diversity) play an important role for multi-hop traffic performance. Our GradPC outperforms other mechanisms in all cases especially when traffic load is heavy (7 flows).

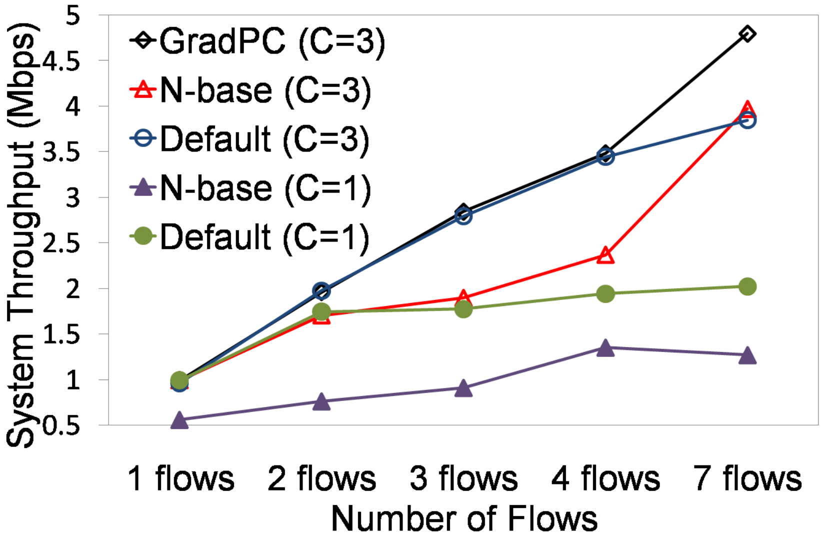
Table 4.1 summarizes the hop count information for the three methods. Our GradPC uses the routes with moderate lengths (neither the shortest nor the longest) in order to preserve both the advantage of power control (increased spatial reuse factor) and channel diversity (decreased inter-hop interference), hence explains the good performance in Fig. 4.3.

Table 4.1: Hop count statistics in a 49-node grid network

| | **GradPC** | **N-base** | **Default** |
|---|---|---|---|
| Total hops | 28 | 42 | 14 |
| Avg. hops | 4 | 6 | 2 |



(a) $C = 3$



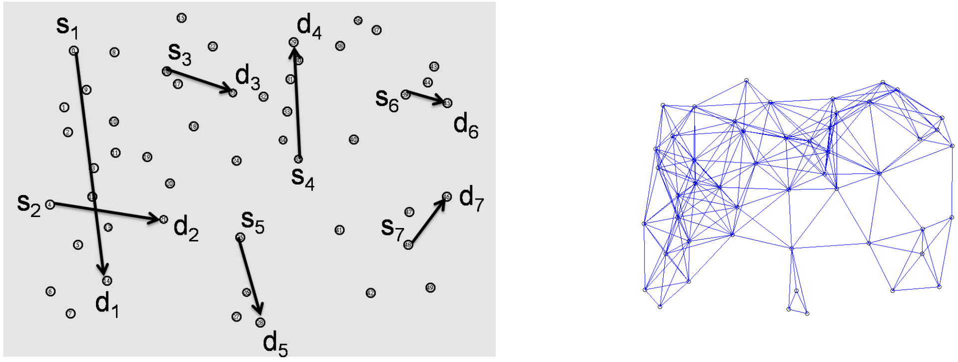
(b) 49 nodes

Figure 4.3: Multi-hop traffic performance in a multi-channel multi-radio grid network.

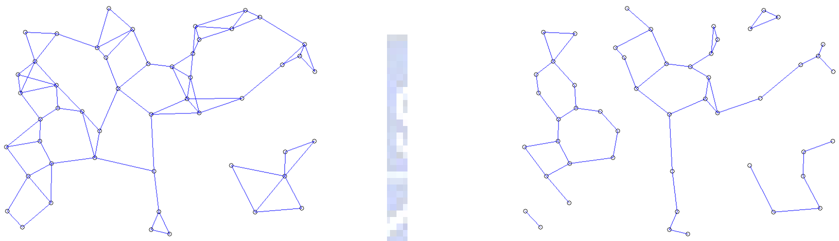
# Chapter 5

# Applying GradPC in Multi-channel Multi-radio Random Topology

We set up a multi-channel multi-radio network with 50 nodes randomly deployed and randomly generate 7 multi-hop flows, as shown in Fig. 5.1(a). Three 802.11b non-overlapping channels are used. The three network topologies produced by our GradPC are illustrated in Fig. 5.1(b)(c)(d) respectively. One more method, **BICONN**, is implemented for providing another power control alternative besides N-base. The BICONN protocol is a power control mechanism proposed by [19]. With multiple channels, BICONN applies the same power reduction for all radios (as the N-base does). We create CBR traffic and increase the sending rate to 11M bps. Fig. 5.2 shows the multi-hop



(a) 7 data flows (b) topology 1



(c) topology 2 (d) topology 3

Figure 5.1: Illustration of node and flow distributions, along with the connected network topologies using GradPC over three channels.

system throughput for different methods as simulation time advances. From this figure, we observe that our GradPC outperforms other methods, and has the highest saturated throughput. Table 5.1 provides the hop count information for all methods. In this case, our GradPC happens to have the same hop count as Default. Nonetheless, since GradPC imposes power gradations on radios, while Default applies the same default transmit power (without power reduction) for all radios, GradPC still yields much better performance than Default, due to higher spatial reuse factor. Moreover, Default is even worse than both N-base and BICONN.

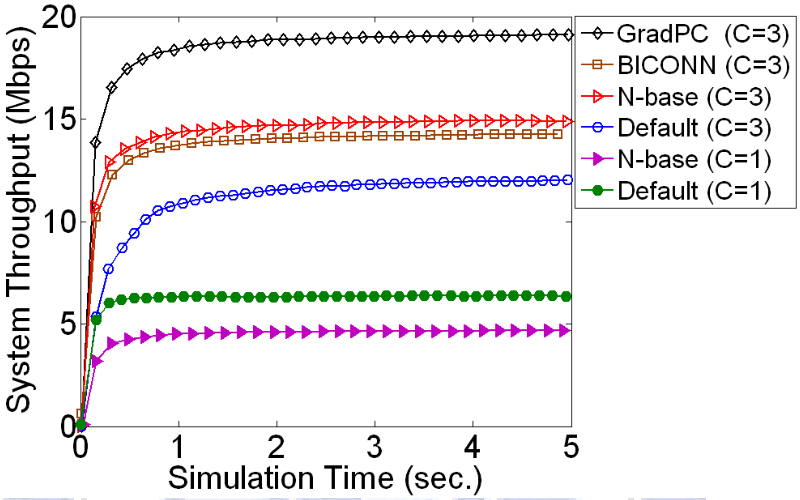


Figure 5.2: Performance comparison of multi-hop traffic in a 50-node random network topology with 7 flows.

Combining all the previous results from both grid and random network topologies, we demonstrate that multi-hop system performance cannot be determined by power parameter or route length alone. Instead, factors such as power, channel, and routing strategy all co-dominate the system performance of multi-hop flows. By seeking tradeoff between those factors, our proposed GradPC framework helps open up more system capacity for multi-hop communications.

Table 5.1: Hop count statistics in a 50-node random network topology

| | **GradPC** | **BICONN** | **N-base** | **Default** |
|---|---|---|---|---|
| Total hops | 21 | 30 | 26 | 21 |
| Avg. hops | 3 | 4.285 | 3.714 | 3 |

# Chapter 6

# Conclusion and Future Work

In this paper, we did a pilot study on the interaction of two physical parameters: power and channel, with the goal of further expanding the system throughput of multi-hop traffic in a wireless ad hoc network. We proposed GradPC and its accompanying route and channel selection protocols. In the current proposal, we adopted the N-base protocol as our power control mechanism to provide the power gradations over radios. However, one may customize other existing power control strategies in place of the N-base protocol. In addition, though the cost of wireless cards has become quite affordable, in some cases it is difficult to install multiple radios at a computing device, due to size consideration or hardware support availability. Thus, how to utilize multiple channels based on the GradPC concept by practically using a single radio may be worth future investigation. This becomes challenging because, in this case, we should carefully deal with both the switching issues and multi-channel hidden-terminal problem, inevitably at the cost of significant control signaling overhead.

The simulation results showed that the proposed GradPC protocol suite yielded the most system throughput than other strategies (including strategy with no power control, and strategies keeping the same channel connectivity degree). By imposing power gradations on radios, and considering route and channel scheduling, our proposed techniques have effectively balanced the multi-hop performance requirements for shorter route and better spatial diversity.

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