

How Much Improvement Can We Get From Partially Overlapped Channels?

Zhenhua Feng and Yaling Yang

Department of Electrical and Computer Engineering

Virginia Polytechnic and State University, Blacksburg, Virginia 24060

Email: {zhenhua, yyang8}@vt.edu

Abstract—Partially Overlapped Channel (POC) based design, has been identified recently as a promising technique to overcome the capacity bottleneck facing wireless engineers in various networks, such as WLAN, Wireless Mesh Network (WMN) and Ad Hoc networks. However, considerable confusions still exist as to the actual power of POCs to improve network capacity, especially since traditional communication system designs treat the so called Adjacent Channel Interference (ACI) as harmful. Based on measurements of actual testbed experiments, we model the impact of POCs on system design and use numerical method to analyze network capacity improvement comparing POC-based design and traditional design. Our investigation shows that for a wide class of network settings, POC-based design allows more flexibility in wireless resource allocation, and can improve overall network capacity by as much as 100%.

I. INTRODUCTION

Partially Overlapped Channels (POCs) refer to wireless channels that have spectrum overlap with other working channels. For example, in the popular IEEE 802.11b/g wireless standard, the largest orthogonal (non-overlapping) channel set includes channel 1, 6 and 11. Other channels are considered partially overlapped with either one or two of these orthogonal channels. These POCs are not used in traditional channel allocation algorithm (e.g. [1] and [2]) due to difficulties in network level interference control. However, the rapid advancement of Software Defined Radio (SDR) and Cognitive Radio (CR) technologies makes the interference control problem of POC easily solvable since these technologies enable nodes to dynamically select their channels based on observations of interference. Hence, motivated by the growing capacity demands of current wireless applications, POCs have emerged as a promising technology to increase overall network capacity by enhancing the spectrum utilization efficiency.

From a signal processing prospective, a closely related concept is the so-called Adjacent Channel Interference (ACI), which refers to the physical signal impairment to one frequency band (channel) due to interference from signal on adjacent frequency bands (channels). The design method of classical wireless communication systems emphasizes on channel separation and orthogonality and considers ACI as hardware and software defects caused by incomplete filtering, improper tuning or poor frequency control. In the innovative POC-based channel assignment schemes, however, spectrum overlapping of different working channels are not considered harmful. Spectrum overlapping in POC-based system can be

a results of ACI. But more generally, we refer to POC-based design as an approach to intentionally employ channels with partially or fully (Co-Channel) overlapped spectrums to take full advantage of all available spectrums. The channel overlap in POC-based design is a natural result of spectrum segmentation/channelization methods being used in the existing systems such as IEEE 802.11b/g. Instead of prohibiting the usage of channels with overlapped spectrum, POC based design let nodes to decide by themselves on whether a specific channel is usable based on their local observations. The primary idea is to provide nodes with full access of all working channels in the available spectrum to increase channel diversity and leverage overall network capacity.

There are a few existing works focused on designing POC-aware channel allocation and scheduling schemes by applying variants of classic network resource allocation schemes. In [5] and [9], Mishra, et al., systematically modeled the POC based network design and discussed several approaches to adapt existing protocols to use POCs. Their discovery showed that POC based design can improve network capacity up to three times in IEEE 802.11b-based networks compared to using only orthogonal channels. In [6], Liu, et al., proposed an genetic algorithm based scheme to meet end-to-end traffic demand by using partially overlapped channels. Their algorithm improved the system throughput. Their simulation results also showed that POC works better in denser networks. In [7], Rad, et al., formulated the joint channel assignment and link scheduling problem as a linear mixed integer problem. Their simulation results showed that there was a significant performance improvement in terms of a higher aggregate network capacity and a lower bottleneck link utilization when all the partially overlapping channels within the IEEE 802.11b frequency band were used.

By adapting POC into classical channel assignment and link scheduling algorithms, these existing schemes successfully demonstrate the benefits of POC in certain simulated network settings. However, their results are limited due to the following reasons,

- 1) Simulations are done in very small scale networks (E.g. [7]) or with specific predetermined topologies (E.g. [6]).
- 2) Classical resource management schemes cannot be directly applied to POC-based design due to unique self-interference characteristics in POC-based design. Formulations in [5], [7], [8] do not address this issue and

potentially lead to incorrect (normally smaller) interference set and thus overestimation of POC's benefits.

In this paper, we present our mathematical models to compute the capacity improvement ratio comparing POC-based designs with traditional designs and address those issues in existing work. The main contributions of our work are as follows,

- 1) We propose two separate optimization models for one-hop and multi-hop networks for POC-based design.
- 2) We evaluate our model with data from real testbed to examine the improvement that POC-based design can bring to practical networks.
- 3) We introduce the orthogonality constraint in our mathematical formulation. Orthogonality constraint is unique to POC-based design and is not found in any existing models.

The rest of this paper is structured as follows. In Section II, we establish the propagation and interference model for POCs. In Section III-A, we introduce our first optimization model and method to compute one-hop network capacity improvement ratio. Next, in Section III-B, we further our investigation to multi-hop data flows. The numerical examples and computation results is presented in Section IV. We conclude our work in Section V.

II. INTERFERENCE MODEL FOR POC BASED WIRELESS NETWORKS

In channel allocation schemes that only use orthogonal channels, it is often unavoidable to assign neighboring nodes with the same channel due to limited number of orthogonal channels. The co-channel interference, hence, prevents these nodes from parallel communications. While POCs can still interfere with each other, it is observed that the received signal power from a sending node is lower if the receiving node uses a POC compared to using the same channel as the sender. Hence, the interference range of POCs is often much smaller than the typical co-channel interference range. Such reduced interference range of POCs enables more parallel transmissions, essentially increasing the capacity of the network as discovered in [5], [6], [7].

We generalize the effect of POCs on wireless channels and use a versatile scaling factor ε_{ij} to capture the effect of POCs in reducing received signal power. ε is determined by the combined effect of different factors, such as radio, propagation, channel separation and coding techniques etc..

Given ε_{ij} and using the general path loss model in [11], we can calculate the received signal power P_r as follows:

$$P_r = P_t K \varepsilon_{ij} \left[\frac{d_0}{d} \right]^\gamma, \quad (1)$$

where K is a constant to reflect the effect of antenna gain and the average channel attenuation, d_0 is a reference distance assumed to be 1-10m indoors and 10-100m outdoors, d is the distance between sender and receiver, and γ is the path loss exponent.

Denote the carrier-sensing range between two nodes that are configured to channels i and j as $r_{cs}(i, j)$. Using Equation (1), we can calculate $r_{cs}(i, j)$ as:

$$r_{cs}(i, j) = d_0 (\varepsilon_{ij} \frac{P_t K}{C S_{th}})^{\frac{1}{\gamma}}, \quad (2)$$

where $C S_{th}$ is the carrier-sensing threshold.

$r_{cs}(i, j)$ essentially represents the interference range between the pair of partially overlapped channels i and j . According to Equation (2), $r_{cs}(i, j)$ is determined by ε_{ij} . Theoretically, $\varepsilon_{i,j}$ can be approximated by calculating the convolution of power spectrum densities (PSDs) of the sending and receiving channels. If two POCs are only different in their center frequencies, ε_{ij} is similar to the I factor introduced in [5] and can be determined by the differences in their channel numbers. This difference in channel numbers is called *channel separation* and is denoted as $\tau = |i - j|$. The carrier-sensing range $r(i, j)$, hence, can be expressed as $r(|i - j|)$ or $r(\tau)$.

When $\tau = 0$, two nodes use the same channel. In such case, $\varepsilon = 1$ and two nodes have the maximum mutual interference range $r(0)$. If two channels are orthogonal, $\varepsilon = 0$ and there is no interference between nodes that are using these channels. If two channels are POCs, $0 < \varepsilon < 1$. The mutual interference range is smaller than the typical co-channel interference range. These relationships are illustrated in Figure 1.

Besides theoretically calculating $\varepsilon_{i,j}$ to derive $r(i, j)$, $r(i, j)$ can also be obtained through field measurements. In this paper, we measured $r_{cs}(|i - j|)$ using the following testbed experiments. We setup two pairs of communicating nodes transmitting on channel i and channel j respectively as shown in Figure 2. Then, we gradually increase the distance between the two communicating pairs and record the interference range, which is maximum distance that the two can affect each other. To reduce measuring error, we did several groups of experiments and took the average. The results is summarized in Table I.

TABLE I
EXPERIMENTAL VALUE OF INTERFERENCE RANGE WITH RESPECT TO CHANNEL SEPARATION τ

channel separation τ	0	1	2	3	4	5
i=1	13.26	9.08	7.59	4.69	3.21	0
i=6	12.89	9.21	6.98	5.15	3.84	0

* interference range is measured in meters

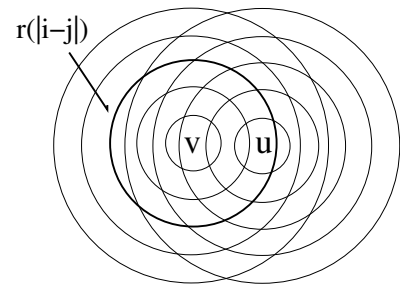


Fig. 1. Node u transmitting on j needs to be in $r(|i - j|)$ to interfere with node v transmitting on channel i

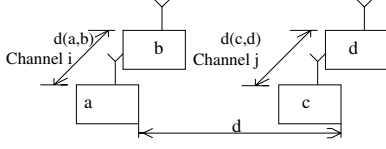


Fig. 2. Illustration of testbed experiment, node pair (a,b) and (c,d) are placed that $d(a,b) \ll d$, $d(c,d) \ll d$

III. MATHEMATICAL FORMULATION TO CALCULATE NETWORK CAPACITY IMPROVEMENT RATIO

In this section, we introduce two optimization models to compute the capacity improvement ratio comparing POC-based designs to traditional designs using only orthogonal channels. The first model is developed for community Wi-Fi networks where each router (cluster head) is connected to a wired network and talks to associated wireless nodes through one-hop connections. The second model is developed for large scale sensor and ad hoc networks where data traffic from a source travels multiple hops to reach its destination.

A. Model I: POC performance in WiFi networks

For generality, we focus on the aggregate one-hop capacity achieved in the network without any assumption on routing and MAC. Note that our analytical model can be easily extended to networks with any specific MAC and routing protocols.

We make the following assumptions. We consider a set of transmitting nodes V distributed in an area A . Each node $v \in V$ communicates through a randomly picked working channel among M available channels denoted as $C = \{1, 2, \dots, M\}$. Among these M channels, N of them are orthogonal denoted by the set $C_{OC} \subseteq C$. The minimum channel separation for two channels to be considered orthogonal is denoted as τ_{th} . We have $N = \lceil \frac{M}{\tau_{th}} \rceil$. In the IEEE 802.11b standard, $M=11$, $N=3$, $\tau_{th} = 5$. All nodes are equipped with radios of similar settings, such as transmission power P_t and carrier sensing threshold CS_{th} , etc. According to the propagation model in Section II, this assumption implies that all radios have the same interference range set $\{r_{cs}(|i - j|)\}$. The set of all potential interfering neighbors of a node $v \in V$ is represented by $S_{int}(v)$. Obviously, $S_{int}(v)$ equals the set of nodes covered in v 's largest interference range $r(0)$.

As illustrated in Figure 3, for each node $v \in V$, we create a companion receiving nodes v' with $d(v, v') \ll d(v, u), \forall v, \forall u$, where $d(u, v)$ denotes the physical distance between any two nodes u and v . The set of companion nodes is denoted as V' . Intuitively, for the new network $G(V, V')$, the maximum aggregate one-hop capacity is achieved when each node $v \in V$ only transmits to its companion node v' . Actually, since there is no concern on routing, we only need to determine the maximum number of parallel transmissions allowed in $G(V, V')$ in each time slot. We define an binary variable $X_i^t(v)$ to indicate the state of node v 's i th channel in

time slot t . Specifically,

$$X_i^t(v) = \begin{cases} 1 & \text{if } v \text{ transmits on channel } i \text{ in slot } t \\ 0 & \text{otherwise} \end{cases}$$

The maximum one-hop capacity over a period of time T is obtained when the maximum number of simultaneous transmission is achieved. Using the channel state index X_i , we can straightforwardly put this into the following objective function.

$$\max \sum_{i=1, \dots, M, v \in V, t \in T} X_i^t(v) \quad (3)$$

Equation 3 successfully transforms the maximum capacity problem into a maximum parallel transmission problem. Next, we introduce some important network constraints for this problem.

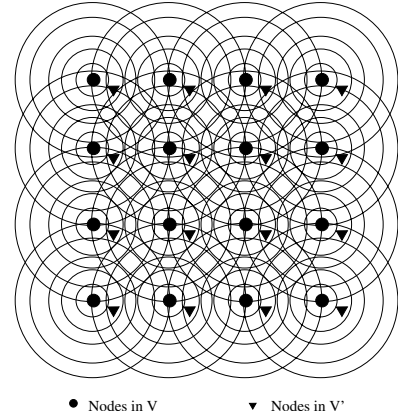


Fig. 3. Topology for computing the One-hop Capacity

Orthogonality Constraint: Orthogonality constraint is a very critical constraint not found in any previous formulation on POC based channel allocation schemes. It captures the fact that two channels on the same node can not be active simultaneously until they are non-overlapping/orthogonal to each other. A lack of this constraint will inevitably lead to infeasible solutions due to strong self-interference. Orthogonality constraint is interpreted as two separate constraints as follow.

Firstly, an active channel i on a node v prevents any channel with overlapped spectrum to be used simultaneously on node v . The set of channels that have spectrum overlap with channel i can be denoted as $POC(i) = \{\max\{1, i - \tau_{th} + 1\}, \dots, \min\{M, i + \tau_{th} - 1\}\}$ where τ_{th} is the minimum channel distance to declare two channels orthogonal. The first part of orthogonality constraint can then be written as

$$\sum_{j \in POC(i)} X_j^t(v) \leq 1, \forall i, \forall v \in V, \forall t, \forall i. \quad (4)$$

Secondly, the maximum number of channels that can work simultaneously on node v should be no larger than the maximum number of non-overlapping channels available to node

v. Mathematically, this is expressed as

$$\sum_{j=1,\dots,M} X_j^t(v) \leq N, \forall v \in V, \forall t. \quad (5)$$

It is noteworthy that, classical channel constraint takes the following form,

$$\sum_{i=1,\dots,M} X_i^t(v) \leq M, \forall v \in V, \forall t. \quad (6)$$

Inequality (6) means the number of parallel transmissions that can be active simultaneously at a node/link is no larger than the number of available channels on this node/link. In POC-based design, since $M \geq N$ is always true, (6) is inherently contained by Constraint (5). As a result, we will not discuss implications of (6) in this paper.

Further investigation shows that constraint (5) can also be removed from the formulation. This is showed in the following lemma.

Lemma 1. For POCs based link-channel scheduling problem stated above, Constraint (4) is a sufficient condition for Constraint (5).

Proof: Since $N = \lceil \frac{M}{\tau_{th}} \rceil$, the remainder of M by N can be computed as $\kappa = M - (N-1) * \tau_{th}$. The M channels thus can be indexed as $I = [1, \dots, \tau_{th}, \tau_{th}+1, 2\tau_{th}, \dots, (N-1)\tau_{th}, (N-1)\tau_{th}+1, \dots, (N-1)\tau_{th}+\kappa]$. With this index method, the M channels are readily divided into N groups each contains at most τ_{th} channels. Namely, they are $I_1 = [1, \dots, \tau_{th}]$, $I_2 = [\tau_{th}+1, \dots, 2\tau_{th}]$, ... If $\kappa \neq 0$ the N_{th} channels group contains less than τ_{th} channels as $[(N-1)\tau_{th}, \dots, (N-1)\tau_{th}+\kappa]$. For each of these channel groups, we have $I[i] \subseteq POC(i)$ which leads to the following inequality.

$$\sum_{j \in I_i} X_j^t(v) \leq \sum_{j \in POC(i)} X_j^t(v) \leq 1$$

Sum up for all N channels, we have

$$\sum_{i=1,\dots,N} \sum_{j \in I_i} X_j^t(v) \leq \sum_{i=1,\dots,N} 1 = N.$$

Q.E.D.

As a results, Constraint (5) is not discussed in the following sections.

Radio Constraint: Radio constraint states that no node can be assigned more simultaneous transmissions or receptions than its maximum number of radios at any time slot. This leads to the following constraint.

$$\sum_{i=1,\dots,M} X_i^t(v) \leq \vartheta(v), \forall v \in V, \forall t, \quad (7)$$

where $\vartheta(v)$ is the number of radios available on node v.

Interference Constraint: We define $S_{int}^{r(\tau)}(v)$ as the set of nodes except node v itself that are covered in the circle of radius $r(\tau)$ and center v. For node v to work on channel i, all potential interferers of node v must keep silent. Specifically, all nodes in $S_{int}^{r(0)}$ must silent their channel i, all nodes in $S_{int}^{r(1)}$

must silent their channel i-1 and i+1, and so forth. This can be expressed as the following constraint.

$$X_i^t(v) + \sum_{\tau=0,\dots,5} \sum_{j \in \{i-\tau, i+\tau\}} \sum_{u \in S_{int}^{r(\tau)}(v)} X_j^t(u) \leq 1, \quad \forall v, \forall i \in M, \forall t \quad (8)$$

The objective (3) and the constraints (4)(7)(8) together constitute a standard Integer Linear Programming (ILP) formulation. Due to the computation complexity, we seek a similar relaxation method employed in [3] and [4] to reduce our ILP to an LP (Linear Program). The fraction of time that v is active on channel i during a given time period T is given by $x_i^T(v) = \sum_{t \in T} X_i^t(v)/T$, $0 \leq x_i^T(v) \leq 1$. $x_i^T(v)$ is continuous function. By summing up both sides of Equations (3)(4)(7)(8) over all time slots $t \in T$ and then dividing the summation by T, we get the following relaxed LP formulation of the original ILP formulation.

$$\begin{aligned} \max \quad & \sum_{i=1,\dots,M, v \in V, t \in T} x_i^T(v) \\ \sum_{j \in POC(i)} x_j^T(v) & \leq 1, \forall i, \forall v \in V, \forall i, \\ \sum_{i=1,\dots,M} x_i^T(v) & \leq \vartheta(v), \forall v \in V, \end{aligned}$$

$$x_i^T(v) + \sum_{\tau=0,\dots,5} \sum_{j \in S_{int}^{r(\tau)}(v), \{i-\tau, i+\tau\}} x_j^T(u) \leq 1, \forall v, \forall i \in M$$

To get the maximum capacity under orthogonal channel based design, we can simply add the following constraint to the above formulation,

$$x_i^T(v) = 0, \forall i \notin C_{OC} \quad (9)$$

where C_{OC} is the set of orthogonal channels.

Assuming $c_{poc}^{one-hop}$ and $c_{oc}^{one-hop}$ are the optimal solution for POC-based and OC-based formulations respectively, we can then calculate the capacity improvement ratio as follow.

$$\eta^{one-hop} = \frac{c_{poc}^{one-hop}}{c_{oc}^{one-hop}} \quad (10)$$

Equation (10) will be used in Section IV for our quantitative analysis.

B. Model II: POC performance in large scale sensor and ad hoc networks

We have already introduced a simple LP formulation in section III-A to calculate the maximum one-hop capacity of wireless networks. This is a nominal capacity that represents the best performance a network can deliver without considerations on routings and MAC. The network traffic is assigned by software to maximize the objective. In large scale multi-hop networks, such as in sensor networks and mesh networks, traffic demand are produced by a set of source nodes and are delivered to a set of destination nodes via multi-hop

connections. The traffic demands on each link, hence, cannot be arbitrarily assigned and is related to routing choices in the network. In particular, as showed in Figure 4, suppose we have a set of source-destination pairs $Q = \{(src(q), dst(q)), q \leq Q\}$ and each pair has a traffic load of $r(q)$ over time period T, we need to compute a channel assignment and link schedule along the paths of flows to deliver all traffic load within time period T. We extend previous model presented in Section III-A to estimate the network capability to fulfill a given traffic demand Q.

We denote by $x_i^T(v, u, q)$ the fraction of time slots that node v transmits to node u on channel i for flow q. We denote by λ the fraction of flow demand that could be delivered over the time period T for any $r(q)$. For each node, $g(v)$ represents the traffic generated from node v. That is

$$g(v) = \sum_{Src(q_i)=v} r(q_i) + \sum_{Dst(q_j)=v} (-r(q_j)),$$

where a node can be the sources or destinations of multiple data flows, or it can be both source and destination for different flows simultaneously. For nodes that only relay traffic, $g(v)=0$. We use $S_c(v)$ to denote the set of nodes that can directly communicate to v. Since two nodes can communicate only when they are on the same channel, $S_c(v)$ is not a function of channel separations and is different from the interference node set $S_{int}^{r(\tau)}(v)$. Finally the model is presented as follow.

$$max \lambda$$

Subject to

$$\sum_{u \in S_c(v)} \sum_{q \in Q} \sum_{\forall i} (x_i^T(v, u, q) + x_i^T(u, v, q)) + g(v) = 0, \forall v \in V$$

$$\sum_{u \in S_c(v)} \sum_{q \in Q} \sum_{j \in POC(i)} (x_j^T(v, u, q) + x_j^T(u, v, q)) \leq 1, \forall i, \forall v \in V$$

$$\sum_{u \in S_c(v)} \sum_{q \in Q} \sum_{\forall i} (x_i^T(v, u, q) + x_i^T(u, v, q)) \leq \vartheta(v), \forall v \in V$$

$$\sum_{u \in S_{int}(v)} \sum_{w \in S_c(u)} \sum_{q \in Q} \sum_{\forall i} (x_i^T(u, w, q) + x_i^T(w, u, q)) \leq 1,$$

$$\forall v \in V$$

$$x_i^T(v, u, q) \geq 0, \forall i, \forall u, v \in V, \forall q$$

The first constraint is the load balance constraint. The second constraint is the orthogonality constraint in multi-hop networks. The third constraint is the radio constraint. The last one is the interference constraint under protocol interference model.

Like in the one-hop case, to get the maximum capacity for orthogonal channel based design, we add an additional constraint,

$$x_i^T(u, v, q) = 0, \forall i \notin C_{OC}, \forall u, \forall v, \forall q. \quad (11)$$

where C_{OC} is the set of orthogonal channels.

Assuming $c_{poc}^{multi-hop}$ and $c_{oc}^{multi-hop}$ are the optimal solution for POC-based and OC-based formulations respectively, we can then calculate the capacity improvement ratio as follow.

$$\eta^{multi-hop} = \frac{c_{poc}^{multi-hop}}{c_{oc}^{multi-hop}} \quad (12)$$

Equation (12) will be used in Section IV for our quantitative analysis.

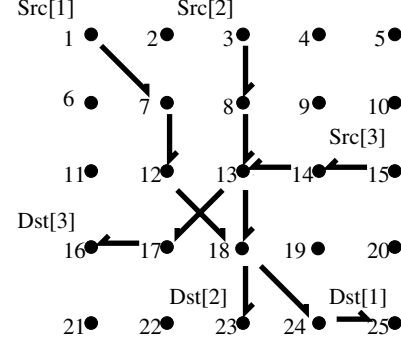


Fig. 4. A sample topology for Model II

IV. NUMERICAL EXAMPLES

In this section, we evaluate our models presented in Section III to compare the performance of POC based design and traditional design. The IEEE 802.11b with 11 Mbps data rate is simulated. Grid and random topologies are used. Nodes are equipped with radios of similar capability and configuration. The communication and interference ranges are set to 100 m and 200 m respectively for all radios. In the grid topology, 64 nodes are distributed on an 8*8 grid. The unit distance of the grid is d. In the random topology, nodes are uniformly distributed in a 1000m*1000m field. Ten independent simulations are performed for each set of network settings and the average over the 10 simulations is used as the final result.

A. Model I

To observe the effect of density on the performance of POC, we measure the capacity improvement ratio against the average number of nodes covered in the co-channel interference range $r(0)$ in the network. In random topologies, this is done by changing the number of nodes added into the area. In grid topology, density is represented by the ratio of interference range $r(0)$ and grid unit distance d. By using results from Gauss's Circle Problem [10], we can calculate the number of nodes covered in $r(0)$ using the following equation,

$$N(d, r(0)) = 1 + 4 \lfloor \frac{r(0)}{d} \rfloor + 4 \sum_{i=1}^{\lfloor \frac{r(0)}{d} \rfloor} \lfloor \sqrt{(\frac{r(0)}{d})^2 - i^2} \rfloor. \quad (13)$$

As a result, we change d to vary the node density. Simulation result is presented in Figure 5. In general, POC greatly improves network capacity by 40% to almost 100%. In the random case, topology plays a primary role on deciding the

performance of POCs. Some scenarios with too dense or too sparse node distributions give much lower improvement ratio. As a results, the overall improvement ratio in the random case is much lower than in the grid case. Another observation is that higher density leads to higher improvement. This trend is not very obvious in random topologies where network topology plays a more important role.

B. Model II

We evaluate Model II in this section. Basically, the network and radio settings are the same as described in Section IV-A. The difference is that we consider a set of data flows $q \in Q$ with source $\text{Src}(q)$ and destination $\text{Dst}(q)$ instead of one-hop transmission. Due to the inherent fairness requirement resulted from the use of scaling factor λ , the improvement ratio is heavily affected by topology. In low density areas, two parts of a network may be connected through a single bridge link. In such topologies, this single bridge link becomes the bottleneck and POC does not have any advantage compared to traditional OC-based channel assignments. In such topologies, capacity improvement ratio is much lower. As a result, the improvement ratios in random topologies are again lower than in the grid topologies. The results are presented in Figure 6 and Figure 7. Figure 6 also illustrates the effect of traffic load. Heavier traffic load tends to give higher network capacity improvement ratio. This is because heavier traffic needs more nodes to transmit and relay and brings more interference into the network. Such heavier interference is better handled by POCs as POCs allow more flexibility in channel choices.

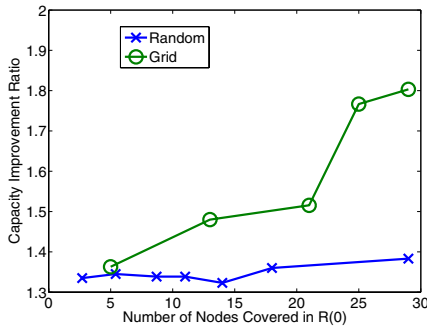


Fig. 5. Capacity Improvement Ratio for Model I

V. CONCLUSION

A few schemes have been proposed recently to integrate POCs into traditional protocol designs. Their simulation results produce very encouraging results on how much improvement POCs can achieve on the overall network performance. However, due to modeling and simulation limitations, the results from these papers are inadequate as an justification for POC-based design. To address these limitations, we introduce a new model with the critical orthogonality constraint and evaluated our model using data from real testbeds in various networking settings that resemble practical networks. Our results show that for a wide range of wireless network settings, POCs are

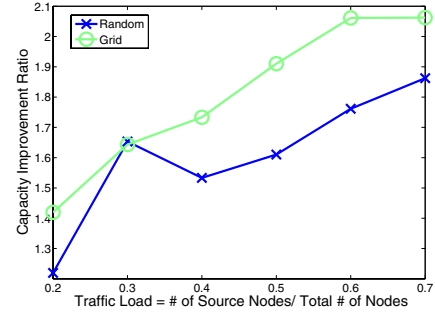


Fig. 6. Capacity Improvement Ratio for Model II

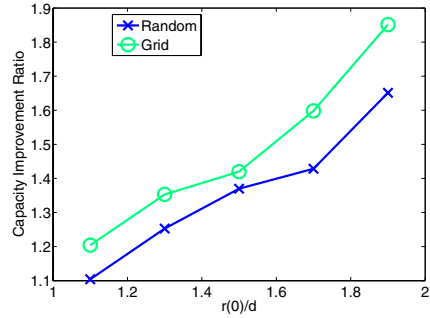


Fig. 7. Capacity Improvement Ratio for Model II

indeed able to leverage network performance by as many as 2 times in 802.11b/g based networks.

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