When Are Directional Antennas Useful in Indoor Environments?

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ABSTRACT

Directional antenna systems can provide two benefits 1) improve signal strength and increase communication range, and 2) improve spatial reuse. Recent work has drawn contradicting conclusions in terms of which of the two benefits dominates in indoor environments. These contradicting conclusions are in fact caused by different levels of contention within the environments used in these studies, i.e., noise-dominated vs. interference-dominated.

In this paper, we first show that due to emerging applications and technologies, wireless networks are becoming interference-dominated, and thus the ability of the directional antennas to improve spatial reuse is becoming critical. Evaluating the benefits of spatial reuse, however, is difficult especially in indoor environments where multipath have both good and bad effect on spatial reuse.

In this paper, we use the *separation metric* to estimate the effectiveness of directional transmission and guide the placement of directional APs in any particular environment. The separation metric summarizes both the angular and the distance separation for a collection of transmissions in a particular environment. We show that this metric, though simple, is powerful enough to capture the various properties of the deployment and the potential interactions among the directional transmissions. Our experimental results show in several scenarios that the separation metric works well in practice.

Categories and Subject Descriptors

C.2.2 [**Computer System Organization**]: Computer-Communication Networks

General Terms

Algorithm, Performance, Measurement

Keywords

Directional Antenna, Wireless Capacity, 60GHz, White-space, Site Planning, Separation Metric

1. INTRODUCTION

Directional antenna systems are becoming commerically available with reasonable pricing, e.g., Phocus Array [1], Xirrus sectored Wi-Fi array [2], Sibeam [3], Ruckus BeamFlex [4], etc. By confining the signal to a narrow region, directional antenna systems can provide two benefits 1) improve signal strength and increase communication range, and 2) improve spatial reuse. Recent work has drawn contradicting conclusions in terms of which of the two benefits dominates in indoor environments. The authors of [10, 11, 7] demonstrated that directional antenna systems are very effective in improving spatial reuse in several indoor experimental settings. However, other work [9] has observed that spatial reuse can be only slightly improved in an indoor testbed presented. These contradicting conclusions are caused by different levels of contention within the environments used in these studies. Specifically, some studies have used noise-dominated testbeds while others have used interference-dominated ones. For example, since the testbed used in [9] is a sparse network (or noise-dominated), the benefits from stronger signal strength dominate over those from spatial reuse.

In this paper, we focus on answering the question of evaluating the effectiveness of directional antennas in terms of spatial reuse in any particular environment. This is especially important in network planning in indoors environments where multipath have both good and bad effect on spatial reuse (Section 4).

Specifically, given any particular environment, we would like to answer the following three key questions.

- Is it worth deploying directional antennas in this particular environment?
- What type of antenna capabilities (e.g. directional or omni-directional and beam-width) should each AP and client have?
- What are the good locations for directional APs in the deployment?

The current network planning practice is to carry out site-surveys with the goal of maximizing coverage, usually with omni-directional antennas. There are two main challenges that cannot be addressed by the current practice: 1) it works well in noise-dominated networks, but not in interference-dominated networks because the goal of maximizing coverage does not consider interference, 2) directional antennas introduce more options for optimization (e.g., orientations) that need to be captured when planning.

In this paper, we use the *separation metric* to answer these questions. The separation metric, which summarizes both the angular and the distance separation for a collection of transmissions in a particular environment, has been introduced in previous work [11] to understand the evaluation results of the directional antenna experiments. In this paper, we show that this metric, though simple, is powerful enough to capture the various properties of the deployment and the potential interactions among the directional transmissions. Our experimental results show in several scenarios that the separation metric has a strong positive correlation with the network capacity, i.e., a higher separation metric indicates a higher network capacity and vice versa. Due to this correlation, we can use the separation metric to estimate the effectiveness of directional transmission and guide the placement of directional APs in any particular environment.

2. MOTIVATION

In this section, we briefly examine existing and two emerging wireless techniques. We show that future wireless networks are going to be interference-dominated and, thus, improving spatial reuse using directional antennas is becoming critical.

2.1 Existing Wireless Networks

Most existing wireless networks, e.g., enterprise and campus networks, have low traffic density and, thus, are noise-dominated. First, the node density is usually low because, in many scenarios, the AP locations are planned and the primary goal of the planning is to ensure coverage. Second, most applications produce bursty traffic partly because the performance of existing wireless networks is not good enough for users to comfortably shift their applications that require high bandwidth to wireless. The experimental setup in [9] is similar to these types of networks. In other scenarios, such as metropolitan areas and in apartment buildings, the node density is significantly higher [6]. Such scenarios are reproduced in studies like [10, 11].

In summary, the traffic density of many existing wireless networks is quite low. This indicates that the main benefits of deploying directional antennas in these networks is stronger signal strength, consistent with the conclusion in [9]. However, we believe that with the emerging wireless technologies, devices, and applications, the traffic density (both the node density and the amount of traffic) will keep increasing.

2.2 Emerging Wireless Techniques

In this section, we examine two emerging technologies: White Spaces and 60GHz.

First, White Spaces are the Ultra High Frequency (UHF) bands between 510 and 700 MHz. Compared to 2.4GHz, the transmission range in these bands is very far, signals do not degrade much, and the antenna size is inherently large (wider antenna beams). Also each AP is expected to service multiple clients due to its communication range and, thus, the aggregated amount of traffic is expected to be high. All these indicate higher level of contention.

Next, recently researchers have started to develop systems for the largely unused 60GHz bands [3]. Compared to 2.4GHz, the transmission range in these bands is very short, reducing the lower level of contention, especially in outdoor environments. However, these devices are primarily designed for indoor environments (rooms) and it has been observed that signals can still reach destinations after reflecting through walls [3], indicating that interference is not confined to LOS even with narrow beams. Also, in terms of node density, it has been envisioned that hundreds of devices will operate in these bands within a small area, indicating extremely high traffic density [5]. At the same time, some applications use the network very heavily, such as high definition video streaming.

In summary, the level of contention is expected to be higher in both White Spaces and 60GHz than in 2.4GHz, due to the signal propagation properties of the White Space spectrum bands and the large number of devices in 60GHz networks. These networks are likely to become interference-dominated and directional antenna systems will be quite useful in optimizing the spatial reuse for these emerging techniques. We leave the quantitative study of the actual benefits in these bands as future work.

3. DIRECTIONAL ANTENNAS FOR SPATIAL REUSE

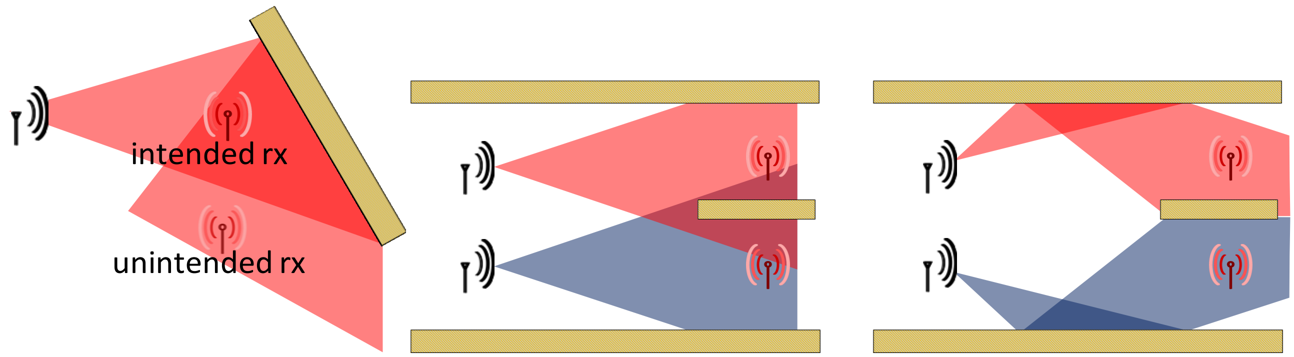
In the previous section, we showed that wireless networks are becoming more interference-dominated. However, due to the rich scattering in indoor environments, it is difficult to estimate the benefits of spatial reuse in any particular indoor environments. This is because the rich scattering (or multipath) have both positive and negative impact on directional antenna systems. Figure 1 shows two examples. In the examples, we consider directional senders and omnidirectional receivers. The directional senders can dynamically orient their beams towards desired directions depending on traffic or interference conditions at the receivers. On the downside (Figure 1(a)), rich scattering may cause unintended interference, i.e., the directional sender is causing strong interference at the unintended receiver through reflectors. On the upside (Figure 1(b)), alternative paths and the obstacles make it possible to reduce interference between transmissions and allow both transmissions to occur concurrently. In this case, the two senders can utilize the reflectors to avoid interfering with each other's transmission. This is in fact impossible to achieve without reflectors and obstacles in the environment.

In this section, we first discuss two main factors that determine the effectiveness of the directional antennas, and provide intuition towards answering the planning questions for directional antennas. Then, we present the challenges in evaluating the factors in any particular environment.

3.1 Factor I: Traffic Density

The first factor is the traffic density, and higher traffic density indicates stronger level of contention. The traffic density in a network is determined by node density, transmission range, traffic patterns, and effects of obstacles.

Node density: Node density is the number of interfering nodes within a certain area. When the node density is high,



(a) Downside (cause unintended interference)

(b) Upside (alternative path to improve spatial reuse)

Figure 1: Downside and upside of rich scattering

the traffic density in the network is high. When the node density is low, the traffic density is low. This is the main difference between the testbeds in [10, 11, 9] that lead to contradicting conclusions.

Transmission range: When the transmission range is long, the traffic density is high, because each sender is expected to contend with more other senders. When the transmission range is short, the traffic density is low.

Traffic patterns: When the applications run on the interfering nodes require high bandwidth, the expected traffic density is high. When all the applications only produce bursty traffic, the expected traffic density is low.

Effects of obstacles: When the signal strength decreases significantly while passing through obstacles, the expected traffic density is low. This is because interference is confined inside each room and the senders in one room may not contend with the senders in another room. When signals do not degrade much passing through obstacles, the expected traffic density is high.

3.2 Factor II: Angular Variability of Interference

The second factor is the angular variability of interference, which is determined by antenna beamwidth and multipath.

Antenna beamwidth: When the antenna beamwidth is narrow, the expected level of contention is low, since senders contend with fewer other senders. When the antenna beamwidth is wide, the expected level of contention is high. This applies to antenna beamwidth on both the APs and the clients.

Multipath: Generally speaking, with higher degree of multipath, the effectiveness of directional antennas will be reduced, because the level of directionality is decreased [7]. On the other hand, the availablity of multiple paths also make it possible for multiple senders and receivers to not interfere with each other (Figure 1).

3.3 Challenges

The current practice to answer the planning questions is to maximize wireless coverage by carrying out site-surveys with omni-directional antennas. The site survey process involves moving one omni-directional AP across all candidate locations with all the clients located at their locations, and collecting signal strength measurements from that AP location to all the client locations. The site survey process can be automated by using a robot [8]. This approach is simple but has two limitations: 1) it does not work well for interference-dominated networks because it ignores the interactions (or interference) among various transmissions, 2) given that directional antennas can dynamically orient the beam towards a direction, there are more options for optimization that are not captured by omni-directional antennas.

Researchers have also used two methods to approach these planning problems for directional antennas: 1) direct measurements of network capacity [10], and 2) emulation based on SINR model [11, 9]. Both these approaches are accurate since they consider interactions among transmissions, but they suffer from poor scalability problem due to high measurement or computation cost.

The naive method of directly measuring the network capacity that can be achieved in each particular environment involves exhaustive measurements and is thus not practical (it takes several hours to take all the measurements for 3 APs in [10]).

The method of using SINR-based emulation can reduce the number of measurements, since it only requires a site survey. The site survey process for directional antennas is similar to that for omni-directional antennas, except when characterizing signal strength between each AP location to each client location, we need to measure every possible combination of antenna orientations of the AP and the client. Basically, for each configuration (i.e., AP location, AP and client orientations), we let the AP broadcast UDP frames to all the clients and measure the mean RSSI between the AP to all the clients. Using this approach, the measurement overhead is significantly reduced, but the computational cost is still high, i.e., exponential in the number of APs. For example, the complexity to find the achievable network capacity is $(K_{AP} * K_C)\binom{N}{1} + (K_{AP} * K_C)^2\binom{N}{2} + \ldots + (K_{AP} * K_C)^N\binom{N}{N}$ where N is the number of APs and K_{AP} and K_C are the number of orientations on APs and clients. This approach takes an extremely long time and a large number of machines to run for one of our experiments with 20 APs and 28 clients.

In summary, existing solutions either ignore the two main factors, or evaluate them in an exhaustive and costly manner.

4. OVERVIEW OF THE SEPARATION METRIC

In this paper, we use the separation metric [11], which summarizes the most important aspects that enable spatial reuse and which at the same time makes the computation manageable (the computational cost is polynomial to the number of APs and clients). Unavoidably, the simplifications to reduce the complexity also reduce the accuracy of the separation metric in predicting the network capacity. In Section 6, we discuss two simplifications and their implications. We also show that even with the simplifications, the separation metric still has a positive and reasonably strong correlation with the network capacity in several experimental scenarios.

There are two steps in computing the separation metric. The first step is the site survey process that characterizes the signal strength from the APs to the clients, as described above. The second step is to compute the separation metric of pairs of transmissions based on the signal strength measurements. While the separation metric is used in [11] as an explanatory tool solely based on its definition, in this paper, we use it as a planning tool based on our experimental results.

After computing the separation metric, it can be used for the following tasks (the three planning questions mentioned in Section 1).

- By comparing the separation metric of different directional antenna configurations, we can estimate and compare the performance (network capacity) of different directional antenna configurations. This is presented in Section 7.1.
- By carrying out measurements or site surveys with different antennas (e.g., with different beamwidths or antenna patterns), we can estimate the performance benefits (network capacity) of these different antennas. This is presented in Section 7.1.
- By comparing the separation metric at different AP locations, we can estimate the locations to place the APs in a particular environment to maximize network capacity or spatial reuse. This is presented in Section 7.2.

There can have several variants of the separation metric definition, based on: 1) whether it is computed from the point of view of an AP, a client, or a link, and 2) whether client-AP association is considered. These different variants have different computational costs and can achieve different levels of accuracy. In our experiments, we find that the separation metric defined on link pairs while considering association is the most accurate. Thus, we only consider this variant in this paper.

Finally, we summarize the scope and the limitations of the separation metric. The goal of the separation metric is to evaluate the network capacity or spatial reuse. This is in contrast to previous work on wireless network planning that only focuses on wireless coverage. The separation metric is designed for interference-dominated networks (such as emerging wireless networks), and it does not work for existing noise-dominated wireless networks. Also, in order to calculate the separation metric, we assume that the locations of the clients are known. Later we will show in Section 7 that exact locations of the clients are unnecessary and some perturbations (1-2m) in client locations are acceptable. Finally, the separation metric is not a tool to predict the actual network capacity in a particular setup because the separation metric depends on the location of the clients, and, thus, it can only be compared within the same environment (e.g., directional vs. omni-directional antennas in the same setup), but not across different environments (e.g., directional antennas in one setup vs. another).

5. SEPARATION METRIC

In this section, we briefly describe the separation metric [11].

5.1 Basic Separation Metric

First, we provide some intuition to motivate the separation metric. Given a pair of links $AP_{i_1} \rightarrow C_{j_1}$ and $AP_{i_2} \rightarrow C_{j_2}$, the potential for spatially reusing spectrum (or "goodness") can be characterized by how well the two links can isolate each other, i.e., can the APs and clients use some orientations to transmit and receive without causing interference at the unintended clients. The separation metric captures this:

$$SEP(i_1, i_2, j_1, j_2) = \max_{k_{i_1}, k_{i_2} \in K_{AP}, k_{j_1}, k_{j_2} \in K_C} S(i_1, j_1, k_{i_1}, k_{j_1}) - S(i_2, j_1, k_{i_2}, k_{j_1}) + S(i_2, j_2, k_{i_2}, k_{j_2}) - S(i_1, j_2, k_{i_1}, k_{j_2})$$

where K_{AP} and K_C denotes the set of orientations on the AP and the client, and $S(i, j, k_i, k_j)$ denotes the signal strength from AP_i to C_j with orientation k_i on AP_i and orientation k_j on C_j.

This metric basically shows the maximum achievable SINR for the two links across all antenna orientations on both APs and both clients. High separation metrics ($>$ 50dB) make it more likely that the two links can successfully receive frames at the same time since the SINR threshold for receiving packets successfully at 54Mbps is 25dB.

The overall "goodness" or separation metric on a collection of APs and clients is:

$$SEP_{BASIC} = \sum_{i_1, j_1, i_2, j_2} SEP(i_1, i_2, j_1, j_2)$$

5.2 Separation Metric with Association

The previous definition of the separation metric [11] does not consider AP-client association, which is an important factor in determining network capacity. So we also introduce the separation metric with association, here we associate each client with the AP with the strongest signal strength. We use $ASSOC(AP_i)$ to denote the clients that associate with AP_i. Then the association version of the separation metric becomes:

$$SEP = \sum_{j_1 \in ASSOC(AP_{i_1}), j_2 \in ASSOC(AP_{i_2})} SEP(i_1, i_2, j_1, j_2)$$

Calculating the separation metrics takes polynomial time.

5.3 Where Does Separation Comes From?

As explained in [11], two components contribute to the separation: distance and angular separation. Distance separation can be achieved if the AP is closer to its intended clients than the unintended clients in signal space. Note that the notions of "far" and "close" apply only in signal space, and may not apply in physical space. For example, we find low correlation in the physical space and the signal space in one experimental setup (Campus). The contribution of angular separation comes from antenna orientations that allow the AP to avoid interfering the unintended clients while maximizes the signal strength at the intended clients.Narrower beam antennas will provide higher angular separation. Also, the angular separation is high if the AP is in the middle of the clients in the signal space. This is because different clients show up in different sectors on the AP. In contrast, angular separation is low if the AP is in the corner of the deployment and all clients show up in a small subset of the sectors of the AP.

6. SEPARATION METRIC AND NETWORK CAPACITY

In Section 4, we showed that the computation of the network capacity is exponential to the number of APs in the network. The separation metric, defined in the previous section, essentially uses several simplifying assumptions to significantly reduce the complexity inherent in computing the network capacity.

In this section, we first discuss these simplifying assumptions. On one hand, these assumptions make the separation metric computationally manageable. On the other hand, they are also the necessary conditions for the separation metric to have a strong correlation with the network capacity. Based on these assumptions or conditions, we also explore when the separation metric does not work. Then we present how well the separation metric is correlated with the network capacity in three indoor environments.

6.1 Necessary Conditions

The first simplifying assumption in separation metric definition is that all APs are actively transmitting at the same time. This is illustrated by the fact that the separation metric for a network is the sum of the separation metric for each link pair. The second simplification is to choose antenna orientations on a pair-wise basis, i.e., on a pair of transmissions.

In fact, both assumptions (or conditions) hold when the level of spatial reuse is high for directional transmission. This indicates that the separation metric is more accurate with higher degree of spatial reuse.

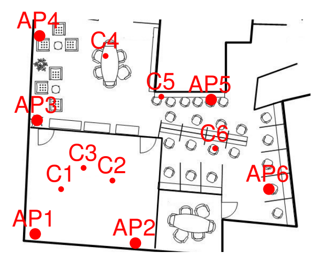
These assumptions raise the question of when the separation metric works and when it does not. As mentioned before, the separation metric works best in scenarios with reasonable level of spatial reuse. In fact, even in networks with low level of spatial reuse, the correlation is still acceptable. However, the separation metric does not work well in noise-dominated networks.

In our experiments, we only used the separation metric to compare the network capacity of network setup with the same set of clients and the same number of APs. We leave the comparison of other scenarios as future work.

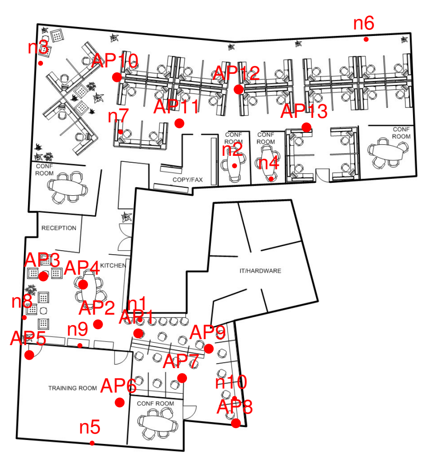
6.2 Correlation With Network Capacity

Figure 3 shows how well the separation metric correlates with network capacity in three indoor scenarios, Campus, Lab 1, and Lab 2, with 4 different APs. The maps for

(a) Campus (large dots: 20 dir/omni APs, small dots: 28 omni clients),



(b) Lab 1 (6 dir/omni APs, 6 dir/omni clients)



(c) Lab 2 (13 dir/omni APs, 10 omni clients)

Figure 2: Experimental maps

Scenario	# APs	# clients	AP ant.	client ant.
Campus	20	28	60°,omni	omni
Lab 1	6	6	35°,omni	4×35°, omni
Lab 2	13	10	60°,omni	omni

Table 1: Experimental setup

Gain (%)	Dir. APs & clients	Dir. APs
Predicted with 6 APs	204	95
Actual with 6 APs	211	75

Table 2: Use separation metric to predict benefits of directional antennas

the three scenarios are shown in Figure 3, and the setup is shown in Table 1. We deploy both omni-directional and directional antennas (various degrees) on APs, and the client directional antenna setup in Lab 2 is the same as that presented in [11]. During the experiments, we did a site survey for each scenario as described in Section 4 (we measure the signal strength from all the APs to all the clients). All the measurements are obtained in 2.4GHz. Using these measurements, we compute both the network capacity using the SINR model (as described in Section 4) and the separation metric. Each subfigure shows the scatterplot and the correlation coefficient ρ between the separation metric and the network capacity. The actual separation metric number (x-axis) has little meaning, since we only use compare data points within the same figure. Note that the correlation coefficient, ρ, equaling 1 indicates a linear relationship, and $\rho = 0$ indicates no correlation (random). The results suggest that even with the simplifications, the separation metric has a positive and reasonably strong correlation with the network capacity, i.e., a higher separation metric indicates a higher capacity compared with a lower separation metric. This can be observed from the shape of the figure and the positive correlation coefficient.

In summary, the separation metric has a positive correlation with the network capacity if it is used to compare scenarios with the same number of APs and with the same scenario. Next, we will apply this observation to answer the questions in directional antenna deployment.

7. USING THE SEPARATION METRIC

In this section, we discuss how the separation metric can help in deploying directional antenna systems. Here, a site survey of signal strength measurements with directional device is necessary due to the lack of a good indoor signal propagation model. We assume a site survey has already been taken place to characterize the target indoor environment.

At the beginning of the paper, we mentioned three key questions:

- Is it worth deploying directional antennas in a particular environment?
- What type of antenna capabilities (e.g. directional or omni-directional and beam-width) should each AP and client have?
- What are good locations for directional APs in the deployment?

Next, we look at answering these questions using the separation metric.

7.1 Estimating the Benefits of Directionality

The first and second questions can both be answered by estimating the performance gains from using antennas with different capabilities, i.e., the benefits of directional APs, directional clients, and directional APs and clients over omni-directional antennas. Given the key observation that the separation metric has a positive and reasonably strong correlation with network performance, we can simply look at the separation metric for different directional antenna schemes. Table 2 shows the predicted improvement of various directional schemes over omni-directional setup in the Lab 1 scenario. The results show that, for 6 APs, the actual improvement is very close to expected.

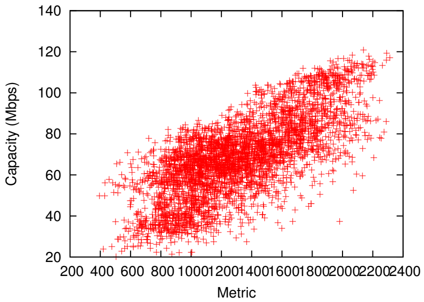
7.2 Finding the Desirable Locations for Directional APs

Suppose the separation metric indicates that deploying directional APs is worthwhile in a particular environment, there is still the challenge of identifying desirable locations for directional APs. Here, we present how to use the separation metric to make this decision. To simplify presentation, we only focus on performance in terms of spatial reuse of spectrum, but ignore other practical factors such as ease of deployment. The problem is to choose the m AP locations out of M candidate locations that maximize spatial reuse. Using the separation metric, the spatial reuse is maximized when $m = M$, i.e., place one directional AP in every candidate location. However, in practice, other constraints such as budget and/or the expected amount of traffic may prevent the network operators from having M APs. Thus we assume that the network operators have already determined m depending on budget and/or the expected amount of traffic (in this case, m is the ratio of expected peak-time aggregated wireless bandwidth to the average wireless bandwidth). The brute force approach using SNR measurements is to run simulation for all possible $choose(m, M)$ AP placement strategies, which is simply too slow.

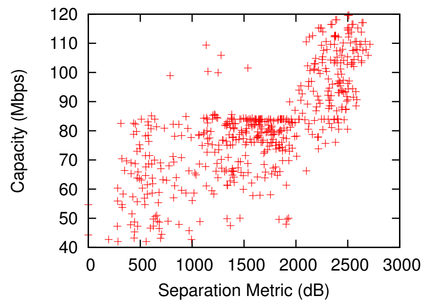
Using the separation metric, we can incrementally include transmissions that maximize the separation metric. In case the predication of the separation metric turns out to be bad, we can also use the naive approach of SINR simulation to verify the choice of AP placement, by simulating the AP placements with the highest separation metric, the next highest, etc., until the k-th highest (k is usually a small constant). We call this approach the MaxSep approach.

For comparison, we look at the AP placement strategy to maximizing "coverage", we call this approach the MaxCov approach, which chooses the set of APs that maximizes the minimum signal strength from all clients. Similarly, SINR simulation can be used here to verify the AP placement with the best coverage, the next best coverage, etc., until the k-th best.

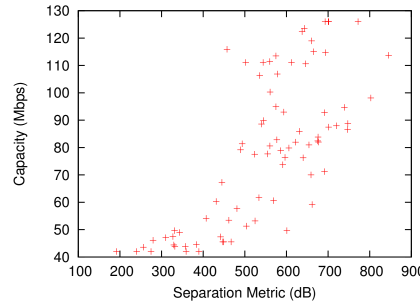
Figure 4 shows the effectiveness of both the MaxSep and MaxCov placement strategies. Each figure shows the best capacity that can be achieved after examining k highest scenarios as a percentage of the optimal capacity. For example, Figure 4(a) shows that for the Campus scenario, MaxCov



(a) Campus (ρ =0.77)



(b) Lab 1 (ρ =0.74)



(c) Lab 2 (ρ =0.73)

Figure 3: Correlation with network capacity

can only achieve 67% of optimal performance if it chooses the AP placement that maximizes the coverage, and MaxSep can in fact achieve 94% of optimal performance. It also shows that for the Campus scenario, even the best network capacity from the top 40 AP placements that maximizes wireless coverage is only 82% of the optimal performance. MaxSep may not always work better though, for example, in Lab2, MaxSep achieves 98% while MaxCov can achieve 100% of optimal performance. The results show that the MaxCov approach does not work well in the Campus scenario and Lab 1 scenario, and MaxSep approach works reasonably well in all scenarios (only 2% difference in Lab2 scenario). Note that MaxSep also implicitly ensures coverge, i.e., for AP deployment that has bad coverage, the separation metric for that deployment will be very low.

7.3 Stability

For planning purposes, we also look at how will small perturbations in time and distance change the separation metric and the network capacity. Figure 5(a)&(b) show how the AP metric change over small perturbations in AP location and time. The results suggest that small perturbations affect separation metric only slightly. Figure 5(c) shows the network capacity before and after we move all the clients in the Campus scenario by 1-2 meters. The results suggest that even though all the users move a bit, the capacity does not change significantly. This is consistent with the observation that small movements result in small changes observed in the separation metric. We can also observe various degrees of changes in the separation metric and capacity in different scenarios, and we leave the further study on perturbations as future work.

8. CONCLUSION

In the first part of this paper, we presented three major factors that determine the effectiveness of directional transmission in any particular environment, and show that for emerging wireless networks, evaluating the spatial reuse for any particular environment is critical. In the second part of this paper, we show that the separation metric, which is a simple measurement based metric for an environment, is strongly correlated with the network capacity of directional antenna systems in that environment. Though the proposed separation metric has limitations, we show that the separation metric is very useful in addressing key problems in planning wireless networks: 1) predicting the benefits of directional antennas in indoors environments, and 2) guiding the placement of directional APs.

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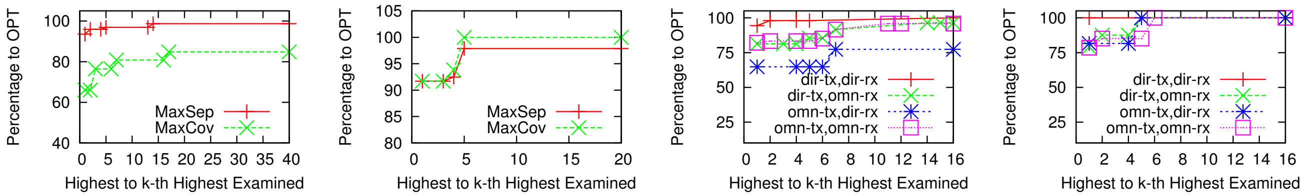
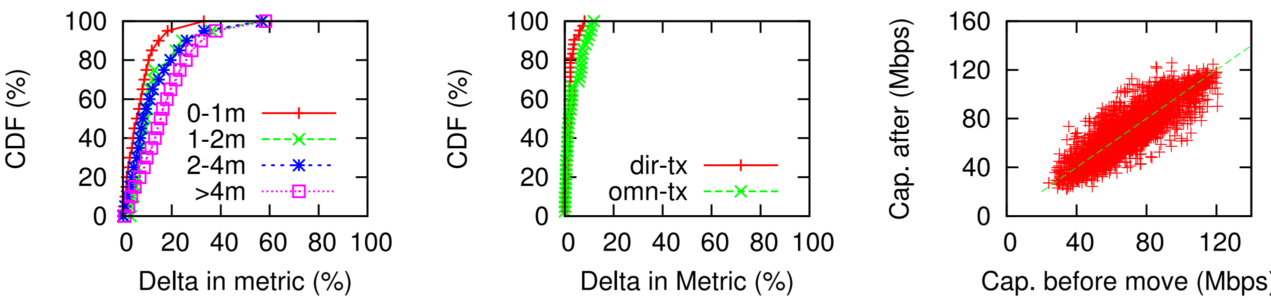


(a) Campus (b) Lab 2 (c) Lab 1 (MaxCov) (d) Lab 1 (MaxSep)

Figure 4: Effectiveness of the planning algorithms



(a) *SEP*,loc (b) *SEP*,time (c) capacity,loc

Figure 5: Changes in separation metric and network capacity with small perturbations in time and space