An Efficient Algorithm for the Optimal Placement of Wireless Extension Points in Rectilineal Wireless Local Area Networks

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Abstract

Wireless Extension Points (EPs) are immobile devices that relay data between the Access Point and the mobile users in a heterogeneous Wireless Local Area Network (WLAN). In this paper, we investigate the optimal placement of EPs such that the throughput capacity of a rectilineal WLAN is maximized. Two channel models are studied, based on the Shannon capacity bound and IEEE 802.11 specifications. We propose an efficient EP placement algorithm that determines the optimal locations of a fixed number of EPs. Our results show that, for a wide range of system parameters, the optimally placed EPs can significantly increase the network throughput capacity. Moreover, we study how the number of EPs, transmission power, path loss exponent, channel models and traffic characteristics affect the optimal EP placement and expected throughput capacity of the network.

1. Introduction

Wireless Local Area Networks (WLANs) provide high-bandwidth Internet access with limited coverage at service hot spots. The latest IEEE 802.11g standard can support bit rates up to 54Mbps. The development of such high bit rate standard was heavily motivated by the demand for content-rich web-based applications. For both real-time and non-real time applications, the user data rate requirements have increased dramatically in recent years. To satisfy the increasing demand of mobile users, new strategies are needed to improve the performance of the WLAN technologies.

A prodigious amount of effort has been spent on improving the capacity of wireless networks within the physical layer. Techniques such as array antennas, space time coding [8], and adaptive beam forming [19] are promising techniques that are often described as the final frontier of wireless communications. However, by using these techniques, the achievable bit rate is still limited by the received signal strength. Since the transmitter power is heavily regulated, little can be done within these techniques to improve the receive signal strength.

To alleviate this problem, an intermediate relay node can be used to boost the power of a wireless signal and in turn improve the network capacity. With slight software modification, commercially available wireless Extension Points (EPs), e.g. D-Link DWL-800AP+ and Linksys WRE54G, which were originally designed as relay nodes to extend the coverage area of an Access Point (AP), can now be used to improve WLAN capacity. EPs are usually immobile, have access to a reliable power source, but do not have direct access to the Internet. An EP helps deliver a packet from the AP to a distanced Mobile Host (MH) by first receiving the packet, and then retransmitting it to the MH. Clearly, since the bit rate between a transmitter and a receiver is a fast decreasing function of the distance between them, by using an EP, the achieved bit rate can be much higher than the original one hop bit rate.

Given immobile relaying nodes similar to EPs, innovative techniques have been proposed in the past, to balance the traffic load [22], to extend the coverage [7], and to enhance the network capacity [2] of wireless networks. However, the potential function of EPs to improve capacity has not received sufficient attention. In particular, the question of how to place the EPs such that the throughput capacity of the network is optimized has not been answered. In this work, we study the throughput capacity improvement of using EPs under two channel models, based on the Shannon capacity bound and IEEE 802.11 data rates under fading. We propose an efficient algorithm to compute the optimal placement of a fixed number of EPs, and study how the number of EPs, transmission power, path loss exponent, channel models and traffic characteristics affect the optimal EP placement and expected throughput capacity of the network.

The rest of this paper is organized as follows. In Section 2, we review the related work in multihop wireless networks. In Section 3, we describe the system model, define the network throughput capacity, derive the design objective of our placement algorithm, and explain the channel models we used in this work. In Section 4, we derive the network throughput capacity with EPs and present the proposed optimal EP placement algorithm. In Section 5, we discuss the effect of different system parameters on the optimal placement of the EPs. Finally, in Section 6, we conclude.

2. Related Work

Inspired by recent advances in ad hoc networking [9], the concept of using peer mobile hosts to relay data has been explored in the context of cellular networks [12]. Based on the approach of using mobile hosts to relay traffic, a routing protocol which emphasize on capacity maximization has been proposed in [14]. In a more recent work, the problem of joint routing, link scheduling and power control in multihop wireless networks was investigated in [3]. Moreover, issues about frequency assignment and frequency recycling in such multihop networks have been addressed in [15].

The concept of using immobile nodes, which are referred to as EPs in this paper, to relay traffic has received relatively less attention. EPs have several advantages when compared with mobile relay nodes. First, since EPs are relatively immobile[1], it is reasonable to assume that they have access to external power supply or have a large built-in battery. Consequently, energy is not a constraint for EPs. Second, since the distance between an AP and an EP is relatively static, links between AP and the EPs should be relatively stable. Furthermore, the sedentary EPs can be configured to their optimal setting which maximizes their benefits.

The issues of using immobile relay node to relay traffic have been discussed in several contexts. In [22], the $iCAR$ architecture uses relay nodes to relay traffic from a congested cell to the less congested neighbor cells. Such relay balances the traffic among cells and in turn improve the system performance. In [4] and [6], the authors proposed to use EPs to increase the coverage area provided by a single AP. In [5], the authors experimentally evaluated the coverage and capacity of a HiperLAN/2 system with EPs. They showed that the modified system not only extends the network coverage but also increases the capacity of the network significantly especially in environments where high attenuation is expected. In [10], the delay aspect of multihop network was investigated. The authors proposed a contention free period leasing scheme based on the IEEE 802.11 PCF mode in a WLAN system with fixed relay nodes. They found that it is possible to support commercial standard voice services with a bounded delay if the number of hops from the AP is small.

From information theory research, the relay channel capacity was studied more than three decades ago in [21], and later considered by [20]. However, the underlying assumptions made in [20] and [21] are not realistic for the wireless medium. Thus, the wireless relay channel capacity was recently derived in [13] and [1].

In [17], the expected throughput capacity of a wireless network with a single-tier relay infrastructure and the optimal placement of the relay nodes were derived based on the latest information theory results. We have shown in [17] that, under the additive white Gaussian noise channel model and with continuous bit rates, the optimally configured relay infrastructure can improve the throughput of a wireless network significantly. However, because of the finite modulation and coding schemes of modern communications systems, transmitters can only transmit in a finite set of bit rates. Moreover, in a wireless channel, multi-path fading has a prominent effect on reliable communication between a transmitter receiver pair. To investigate the effect of relay infrastructure on network capacity in a practical wireless communications system is the main focus of this work. In particular, we explore the option of using commercially available extension points to perform network layer relay with the objective of improving the network throughput capacity. In addition, this paper considers a multi-tier EP architecture.

3. Relaying Strategy and Design Objectives

The system under consideration is analogous to a Basic Service Set (BSS) of an IEEE 802.11 WLAN. In this network configuration, an AP is connected to the wired network. In a network with no EP, MHs which are located within the AP's coverage area directly communicate with the AP. In a network with EPs, mobile hosts located at different locations are associated with either the AP or a suitable EP. If a MH is associated with an EP, this MH will treat the selected EP as an AP and only communicate with the EP. In other words, the EP relays the packets between the AP and the MH, and there is no direct communication between the AP and the MH. When the MH moves to another location, it may have to "handoff" and associate with another EP.[2]

[1] They can be moved to follow large time-scale network traffic variations.

[2] The handoff algorithm is beyond the scope of this work.

The AP communicates with each MH in its coverage area in a round robin fashion, thus dividing the time axis into time-varying *cycles*. In each cycle, the AP transmits a downlink packet to the chosen MH, and the MH transmits a uplink packet to the AP. For both uplink and downlink, if the MH is associate with an EP, the packets are relayed via the EP. In this study, we assume the length of the uplink packets and the length of the downlink packets are unequal but are fixed, and the AP always has a packet to send to each MH and vice versa.

We assume the transmission schedule for all transmitters is decided perfectly by the AP, and communication is performed in a poll-and-response fashion. Thus, we can model this as a single-channel fully-connected network. In other words, at any given time, only one transmitter is allowed to transmit, so that no interference is experienced at any receiver, and no collision can occur.

Let x be the total number of bits of an uplink and a downlink packet. Let T_i represent the packet transaction time of an AP-MH pair in the i^{th} cycle. By the law of large numbers, the throughput capacity of the network is

$$C = \lim_{n\to\infty} \frac{nx}{\sum_{i=1}^{n} T_i} = \frac{x}{E[T_i]} \quad . \tag{1}$$

Therefore, in order to maximize the throughput capacity of the network, $E[T_i]$ needs to be minimized. Thus, the design objective of our system is to minimize the expected time that an AP-MH pair completes a single downlink-uplink packet exchange, which we call the expected packet transaction time in this paper.

The packet transaction time is inversely proportional to the communication rate between a pair of transmitter and receiver. Since different random network parameters such as the distance between the transmitter and receiver and channel fading affect the reliable communication rate, the packet transaction time is random. In this paper, two transmission rate models are used: 1) the Shannon capacity bound for a point-to-point Gaussian channel, and 2) the IEEE 802.11g physical layer model under Rayleigh fading. For both models, the following propagation path loss model is used [16]:

$$P_2 = \frac{P_1}{d_2^{\alpha}} \quad , \tag{2}$$

where P_1 is the reference signal power measured at 1 meter away from the transmitter, P_2 is the signal power measured at d_2 meters away from the transmitter, and α is a positive constant representing the path loss roll off factor.

In the following subsections, we describe how the two transmission rate models are used to determine the transmission time of a packet.

3.1. Shannon Capacity Bound

In this ideal model, the bit rate between a pair of transmitter and receiver is represented by the Shannon capacity for a point-to-point Gaussian channel. We assume that the noise variance, N_t, is the same anywhere in the network. Let the signal power received by a receiver be P_r and the available bandwidth be W. The channel capacity is $Wlog_2(1+\frac{P_r}{N_t})$ bps [11]. If the transmitter reference power is P, while the distance between the transmitter and receiver is l, by using (2), the bit rate between this transmitter and receiver is $Wlog_2(1+\frac{P}{l^{\alpha}N_t})$ bps. If the transmitter has x bits to transmit to the receiver, the data transaction time is

$$T_s(l,P,x) = \frac{x}{Wlog_2(1+\frac{P}{l^{\alpha}N_t})} \text{ seconds} \quad . \tag{3}$$

In this work, when this model is used, we assume the transmitter always knows the transmission rate that it is allowed to used, and no transmission error will occur.

3.2. IEEE 802.11g under Rayleigh Fading

Suppose there are M data rates, denoted as $r_1, r_2, ..., r_M$, supported by the physical layer. Reliable communication by using rate r_m can be realized only if the signal strength at the receiver is above a certain threshold, say η_m. Consequently, for the set of M data rates, there is a set of M thresholds, $\eta_1, ..., \eta_M$, and we further define $\eta_0 = 0$ and $\eta_{M+1} = \infty$. For IEEE 802.11g, there are 11 different physical communication rates, and the minimal threshold for each bit rate is specified by the standard.

Under Rayleigh fading, the instantaneous power, γ, is exponentially distributed with the probability density function $p(\gamma) = \frac{1}{P_r}e^{\frac{-\gamma}{P_r}}$, where P_r is the average power of γ. Consequently, the probability that a transmitter with reference power P can transmit at rate r_m, to a receiver at distance l is $p(r_m,l,P) = \int_{\eta_m}^{\eta_{m+1}} \frac{l^{\alpha}}{P} e^{\frac{-\gamma l^{\alpha}}{P}} d\gamma$ where $m = 1,2,...,M$ and $l > 1$. Furthermore, in some instances, the receiver can be located in a deep faded area, i.e., is experiencing bad channel condition. The probability of these instances, where the transmitter cannot transmit in any data rate, is $p_f(l,P) = \int_{\eta_0}^{\eta_1} \frac{l^{\alpha}}{P} e^{\frac{-\gamma l^{\alpha}}{P}} d\gamma$, while the probability that the transmitter can transmit successfully is $p_s(l,P) = 1 - p_f(l,P) = \sum_{m=1}^{M} p(r_m,l,P)$.

Unlike the ideal Shannon bound model, in the discrete-rate model with fading, the transmitter needs a small channel probing time, denoted T_{prob}, to test the channel and decide the transmission rate before the actual data transmission can take place. If the transmitter determines that the channel condition does not allow it to transmit at any rate, it will give up its transmit opportunity, and prob the channel again later. This extra channel probing time add to the total packet transaction time.

Let $T(l, P, x)$ be a random variable that represents the transaction time of an x bit packet, and let S and F be the events of "good" and "bad" channel states respectively. The expected data transaction time is

$$\begin{aligned} E[T(l,P,x)] &= E[T(l,P,x)|F]p_f(l,P)+ \\ &\quad E[T(l,P,x)|S]p_s(l,P) \\ &= [E[T(l,P,x)] + T_{prob}]p_f(l,P)+ \\ &\quad \left[\sum_{m=1}^{M} \frac{p(r_m,l,P)}{p_s(l,P)} \left[\frac{x}{r_m} + T_{prob}\right]\right] \times p_s(l,P). \end{aligned} \tag{4}$$

Rearranging the above, we have

$$T_g(l,P,x) = E[T(l,P,x)] = \frac{T_{prob}}{p_s(l,P)} + \sum_{m=1}^{M} \frac{p(r_m,l,P)}{p_s(l,P)} \frac{x}{r_m} \quad . \tag{5}$$

4 Optimal Placement of EPs

4.1 EP Relaying Strategy

In the simplest scenario, we have a single MH and one EP, on a half-line where the AP is at the origin, and the following system parameters.

- x_d = downlink packet length (bits).
- x_u = uplink packet length (bits). Let $x = x_d + x_u$.
- $\beta = \frac{x_d}{x_d + x_u}$ = proportion of downlink data.
- α = path loss roll off factor.
- P_{ae} = reference power of AP or EP.
- P_m = reference power of MH.[3]
- d = location of EP.
- l = location of MH. ($d < l$)

If the MH does not use the EP, the expected time required to complete data transaction is

$$T_{noep}(l) = T(l, P_{ae}, x_d) + T(l, P_m, x_u) \tag{6}$$

where T can be either T_s or T_g.

Now, suppose the MH decides to use the EP to relay its packet. The expected time required to complete the transaction is

$$\begin{aligned} T_{ep}(l,d) = T(d,P_{ae},x_d) + T(|l-d|,P_{ae},x_d)+ \\ T(d,P_{ae},x_u) + T(|l-d|,P_m,x_u). \end{aligned} \tag{7}$$

By using an EP, the same data has to be transmitted twice. As a result, the EP may or may not be beneficial to a MH. Therefore, before a mobile host transmits, it has to decide whether to use the EP to facilitate its communication with the AP, or communicate with the AP directly. This decision is made based on the expected packet transaction time. In other words, a MH will use an EP to facilitate its communication with the AP only if such usage results in a smaller expected packet transaction time.

When fading is involved in the communication model, the effect of using the EP varies from time to time. In some instances, it is more beneficial for a MH to communicate with the AP via the EP, while the same may not be true in other instances. Ideally, it is beneficial for the MH to explore this time varying nature of the channel, and made its decision opportunistically. However, from the implementation point of view, it is difficult to estimate and compare the channel conditions at all potential receivers on a per packet basis. Moreover, it takes time to associate a mobile host to an EP. By the time such "handoff" and association process has completed, the channel condition may have changed. Thus, in this work, we assume that a MH will always use an EP to facilitate its communication with the AP if such usage shortens the *expected* packet transaction time.

For the rest of this paper, we consider the multi-user, multi-EP case, and compute the optimal EP placement in an one-dimensional WLAN model. One-dimensional WLAN systems are expected to be installed along streets, roads and other outdoor urban environments in the near future.

4.2. Multiple Extension Points

In this scenario, we assume that a fixed number, $2N$, where $N > 1$, of extension points are available for each AP in the WLAN system. Fig. 1 shows a simple example, where there are 3 EPs available on the right hand side of the AP[4]. A vector, $\underline{d}$, is used to represent the displacement of EPs with respect to the AP. The displacement of the N EPs to be installed on the right hand side of the AP can be represented as

[3] Since the AP and EP are immobile, it is reasonable to assume that they have access to external power supply or are equipped with a high capacity battery. Consequently, in our system model, it is reasonable to assume that $P_m \leq P_{ae}$.

[4] Because of symmetry, we can ignore the left hand side of the system in our discussion.

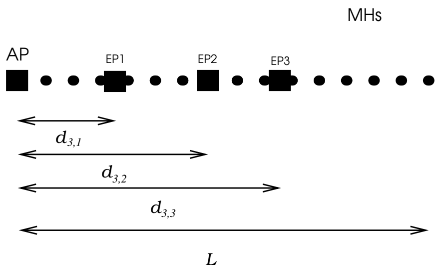

Figure 1. One-dimensional network with multiple EPs.

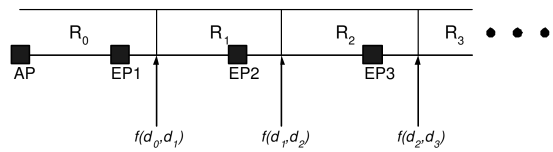

Figure 2. Continuous service regions for different EPs.

$\underline{d} = [d_{N,1}, d_{N,2}, ..., d_{N,N}]$, where $0 < d_{N,1} < d_{N,2} < \cdots < d_{N,N} < L$.

The MHs are uniformly distributed from $0+\epsilon$ to L meters away from the AP. An MH may either communicate with the AP directly or select the most suitable EP, which can result in the shortest expected packet transaction time, and communicate with the AP via the selected EP. Given a fixed placement of the EPs, $\underline{d}$, the expected packet transaction time of the network, $\overline{T_{ep}(\underline{d})}$, is

$$\int_{0+\epsilon}^{L} \frac{1}{L} \min(T_{noep}(l), T_{ep}(l, d_{N,1}),\ ..., T_{ep}(l, d_{N,N}))dl. \tag{8}$$

Using (8), we can cast the optimal EP placement problem as the following optimization problem.

$$\text{Objective: } \min_{\underline{d}} \ \ \overline{T_{ep}(\underline{d})} \tag{9}$$

$$s.t. \ \ 0 < d_{N,1} < d_{N,2} < \cdots < d_{N,N} < L \quad .$$

Clearly, this problem is difficult to solve directly. In the following subsection, we discuss the special characteristics of this problem and present a simplified reformulation.

4.3. Problem Reformulation

We first show that each EP is responsible to serve a continuous segment of the network. Then, the minimization function inside the integral of (8) can be removed by taking the integration segment by segment. This simplifies the analysis and eventually facilitates the development of a computationally feasible algorithm that solves the optimization problem in (9).

Theorem 1 *Given $T(l, P, x)$, where T represents either T_s or T_g, is an increasing and convex function of l, where l is within the region of interest, for any two EPs, EP$_i$ and EP$_j$, which are located at d_i and d_j respectively, where $i < j$ and $d_i < d_j$, there exists an $l^* > \frac{d_i+d_j}{2}$ such that $\forall\ l > l^*$, $T_{ep}(l, d_i) > T_{ep}(l, d_j)$ and $\forall\ l < l^*$, $T_{ep}(l, d_i) < T_{ep}(l, d_j)$.*

Due to page limitation, the proof of this theorem is given in [18]. Moreover, it can be shown that, for the system parameters under consideration, $T_s(l, P, x)$ and $T_g(l, P, x)$ are convex. The region of convexity of $T_s(l, P, x)$ and $T_g(l, P, x)$ and their effects on the proposed optimization algorithm is further discussed in [18].

Hence, by Theorem 1, for any two adjacent EPs, EP$_i$ and EP$_j$, where $d_i < d_j$, there exists an l^* that divides the service regions of this two EPs. Since l^* is a function of d_i and d_j, let us rename l^* to $f(d_i, d_j)$. For all $l < f(d_i, d_j)$, the MHs are serviced by the EP$_i$ (or not serviced by any EP if the MH is very close to the AP), while the rest of the network is serviced by EP$_j$. Similarly, if another EP is placed at d_k, where $d_j < d_k$, there exist a $f(d_j, d_k)$ that divide the service regions of EP$_j$ and EP$_k$. As a result, the service region of EP$_j$ is from $f(d_i, d_j)$ to $f(d_j, d_k)$. Fig. 2 describes a simple example, which illustrates the service regions corresponding to the network in Fig. 1. R_1, R_2, R_3 are the service regions of EP1, EP2 and EP3 respectively. Notice that, if an EP is placed at the AP, $d_0 = 0$, the system is unchanged. Thus, R_0 denotes the service region serviced directly by the AP. We denote the border between regions R_i and R_{i+1} as $f(d_i, d_{i+1})$.

Then, for a given EP placement $\underline{d} = [d_{N,1}, ..., d_{N,N}]$, and letting $d_{N,0} = 0$, (8) can be rewritten as

$$\begin{aligned}\overline{T_{ep}(\underline{d})} &= \int_{0+\epsilon}^{L} \frac{1}{L} \min(T_{noep}(l), T_{ep}(l, d_{N,1}),\ ...\ , T_{ep}(l, d_{N,N}))dl \\ &= \frac{1}{L} \Bigg(\int_{0+\epsilon}^{f(d_{N,0}, d_{N,1})} T_{noep}(l)dl + \\ &\qquad \sum_{i=1}^{N-1} \int_{f(d_{N,i-1}, d_{N,i})}^{f(d_{N,i}, d_{N,i+1})} T_{ep}(l, d_{N,i})dl + \\ &\qquad \int_{f(d_{N,N-1}, d_{N,N})}^{L} T_{ep}(l, d_{N,N})dl \Bigg) .\end{aligned} \tag{10}$$

Since it is not possible to obtained a closed form for $f(d_{N,i-1}, d_{N,i})$, the gradient of this objective with respect to $\underline{d}$ is still hard to compute. However, by using (10), we can obtain some characteristics about the gradient of $\overline{T_{ep}(\underline{d})}$. We simplify (10) further in the following. Let $TM_{noep}(l) = \int T_{noep}(l)dl$ and $TM_{ep}(l, d_{N,i}) = \int T_{ep}(l, d_{N,i})dl$.

$$\overline{T_{ep}(\underline{d})} = \frac{1}{L}[TM_{noep}(f(d_{N,0}, d_{N,1})) - TM_{noep}(0+\epsilon) + \sum_{i=1}^{N-1} TM_{ep}(f(d_{N,i}, d_{N,i+1}), d_{N,i}) - \sum_{i=1}^{N-1} TM_{ep}(f(d_{N,i-1}, d_{N,i}), d_{N,i}) + TM_{ep}(L, d_{N,N}) - TM_{ep}(f(d_{N,N-1}, d_{N,N}), d_{N,N})]. \quad (11)$$

From (11), it is clear that $\frac{\partial \overline{T_{ep}(\underline{d})}}{\partial d_{N,1}}$ is a function of $d_{N,1}$ and $d_{N,2}$ only, $\frac{\partial \overline{T_{ep}(\underline{d})}}{\partial d_{N,i}}$ is a function of $d_{N,i-1}$,$d_{N,i}$, and $d_{N,i+1}$ only, for $1 < i < N$, while $\frac{\partial \overline{T_{ep}(\underline{d})}}{\partial d_{N,N}}$ is a function of $d_{N,N-1}$ and $d_{N,N}$ only. The important implication from this is that, given $d_{N,i-1}$ and $d_{N,i+1}$, the rate of change of $\overline{T_{ep}(\underline{d})}$ with respect to $d_{N,i}$ does not depend on the position of the other EPs. For a global minimum, $\frac{\partial \overline{T_{ep}(\underline{d})}}{\partial d_{N,i}}$ $\forall i \;\; s.t. \;\; 1 \leq i \leq N$ must be equal to zero.

In the next subsection, we present a simplified algorithm to solve the optimization problem using the above result.

4.4. Optimization Algorithm

We discretized the network space into n equally spaced portions, each of which is an EP candidate site. Each candidate site is indexed from 1 to n according to their distance from the AP. Then, the objective is to choose N out of n EP candidate sites such that the expected throughput capacity of the network is maximized.

Since the optimal location of an EP only depends on the locations of its adjacent EPs, we can treat this problem as a sequence of 2-EP and 3-EP placement problems. First, we can obtain the full characteristics of the 3-EP and 2-EP networks. Then this information can be used recursively to determine the optimal placement of the EPs in an N-EP network.

The following three sets of values for the 2-EP and 3-EP networks are first computed numerically.

$$\begin{aligned} a(x) &= \text{Optimal } d_{2,1} \text{ given } d_{2,2} = x \\ b(x,y) &= \text{Optimal } d_{3,2} \text{ given } d_{3,1} = x \text{ and } d_{3,3} = y \\ c(x) &= \text{Optimal } d_{2,2} \text{ given } d_{2,1} = x \\ & \quad \forall x, y \in [1, n] \end{aligned} \quad (12)$$

Then a recursive search is carried out as shown in Fig. 3. In this algorithm, *ep_placement* is an array with N elements which represent the optimal EP locations. The function *optimal* is an recursive function that is used to search for all the local minimums. If the algorithm returns more than one output, we evaluate all of them and choose the global minimum.

```
for x = 1 to n
    ep_placement(1) = a(x)
    ep_placement(2) = x
    optimal(ep_placement,3)
end

function optimal(ep_placement, ep_num)
for i = ep_placement(ep_num-2)+1 to n
    if (b(ep_placement(ep_num-2),i)==
        ep_placement(ep_num-1))
       ep_placement(ep_num) = i
       if ep_num<N
          optimal(ep_placement, ep_num+1)
       else
          if (c(ep_placement(N-1))==
              ep_placement(N))
             output ep_placement
             return
          end
       end
    end
end
```

Figure 3. Optimal EP placement searching algorithm.

5. Numerical Analysis

In this section, we discuss the benefit of the optimally placed extension points with respect to different channel models and system parameters. Both of the two channel models described in Section 3.1 and Section 3.2 are used. In addition, the system has four system parameters: roll off factor (α), proportion of downlink data (β), power of the AP and EP over power of MH ratio (P_{ae}/P_m), and the number of EPs (N). By using a particular channel model, for each set of parameters, there is an optimal placement of EPs and two capacities: C_{noep} and C_{ep}, where C_{noep} represents the throughput capacity of the network without extension points, while C_{ep} represents the throughput capacity of the network with the extension points optimally placed. Thus, from (1), C_{noep} and C_{ep} are defined as $\frac{x}{T_{noep}}$ and $\frac{x}{T_{ep}(\underline{d^*})}$ respectively, where $\underline{d^*}$ represents the optimal location(s) for the EPs. We define the performance gain of the network as

$$Gain = \frac{C_{ep} - C_{noep}}{C_{noep}} \quad (13)$$

For a particular set of system parameters, two different optimal EP placements can be computed under the two channel models. Let $\underline{d_S} = (d^S_{N,1}, ..., d^S_{N,N})$ and $\underline{d_G} = (d^G_{N,1}, ..., d^G_{N,N})$ be the optimal EP placements obtained by using the Shannon model and IEEE 802.11g model, respectively. The average placement difference between the two channel models is defined as

$$D = \frac{1}{N} \sum_{i=1}^{N} \frac{|d^S_{N,i} - d^G_{N,i}|}{d^S_{N,i}} \tag{14}$$

In the following, the relationship among the system parameters with respect to the optimal EP placement and performance gain with different channel models will be discussed.

5.1. Roll Off Factor

We study the effect of the roll off factor (α) and the number of EPs (N) with both channel models in Fig. 4, Fig. 5 and Fig. 6. The network provide a 400 meters coverage area. Both the AP and EP are equipped with a 10dBm transmitter, while the mobile hosts use a 5dBm transmitter. All transmitters and receivers have 2.2dBi antenna gain. The network occupies a 20MHz channel in the 2.4 GHz spectrum, and a -90dBm noise power is assumed anywhere in the network. The combined length of a uplink and a downlink packet is set to 2kbyte, and 70% of downlink traffic is assumed.

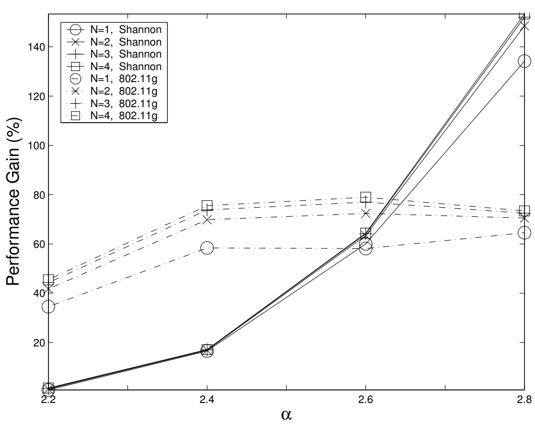

Figure 4. Optimal performance gain with respect to different roll-off factors.

Fig. 4 and Fig. 5 show the performance gains and optimal EP placements with respect to different roll off factors respectively. By using the Shannon point-to-point channel model, when the roll off factor is low, the entire network can transmit at very high rates; thus, the beneficial effects of the EPs are small. As shown in Fig. 5, when the EPs are optimally placed, they are located very close to the edge of the network so that they can only help the small segments of the network which have the worst throughput. As a result, the beneficial effects of the EPs are insignificant. The roll off factor determines how fast the signal decades as it travels. As the roll off factor increases, the beneficial effects of the EPs increase. For a high roll off factor, the optimally placed EPs are more spread out. This means each EP is assigned to help a longer segment of the network when they are optimally placed. Consequently, the performance gain increases as the roll off factor increases.

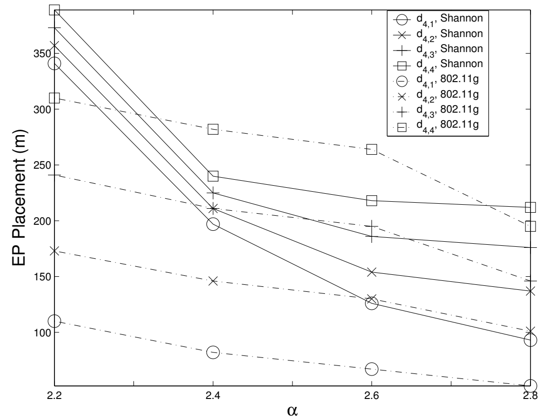

Figure 5. Optimal placement of 4 EPs with respect to different roll-off factors.

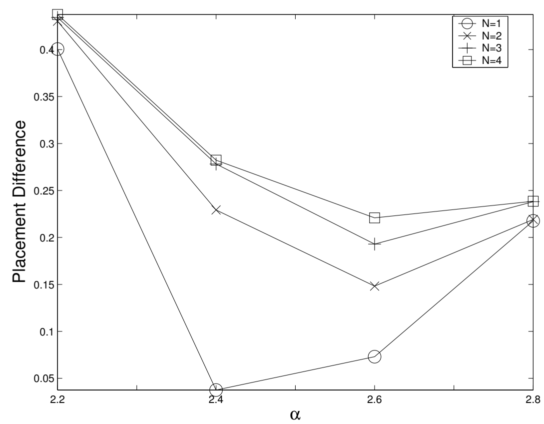

Figure 6. Average placement difference between the two channel models with respect to different roll-off factors.

Under the IEEE 802.11g model, some different trends are observed. As shown in Fig. 5, when the roll off factor is large, the EPs are located closer to each other and to the AP. This implies that the distanced MHs receive less benefit from the EPs when the roll off factor is large. This counter intuitive result suggests that when the roll off factor is large, it is more beneficial to allocate more EPs to help MHs that are relatively closer to the AP.

From Fig. 4, when the roll off factor is small, the performance gain increases as the roll off factor increases. When the roll off factor is large, under 802.11g with Rayleigh fading, the performance gain decreases as the roll off factor increases. In a high channel attenuation environment, it is very hard to maintain high throughput at the edge of the network. Therefore, as the roll off factor increases, the EPs can only prevent the network throughput from degrading further, but cannot provide high throughput improvement.

By using both channel models, the effect of diminishing return is observed as the number of EPs increases. Such phenomenon is more obvious under the Shannon point-to-point model or when the roll off factor is low.

In Fig. 6, we observed that the optimal placements obtained under the two channel models are quite different. In general, the placement different increases as the number of EPs increases. In this study, the Shannon point-to-point channel model is used to approximate the achievable bit rates of future WLANs. This results suggests that the optimal placements of the EPs will change if the AP and EPs are upgraded to a new WLAN standard which can achieve bit rates closer to the Shannon capacity bound.

5.2. Proportion of Downlink and Uplink Traffic

We study the effect of the proportion of downlink data (β) and the number of EPs (N) on an outdoor network with both channel models in Fig. 7, Fig. 8 and Fig. 9. The system parameters are identical to the previous subsection except the roll off factor is set to 2.6 and the combined length of a uplink and a downlink packet is set to 2kbyte.

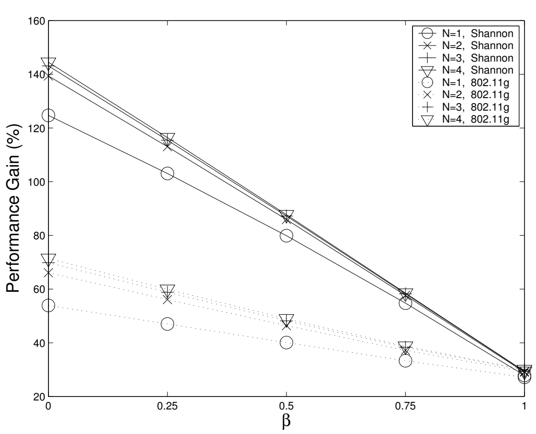

Figure 7. Optimal performance gain with respect to proportion of downlink data.

From Fig. 7, the performance gain increases as the proportion of uplink data, $(1 - \beta)$, increases. This is, again, because the MH's transmitter has less power compared with that of the AP and EPs. As the amount of data needed to be transmitted by the MH's transmitter increases, the beneficial effect of the EP becomes more and more significant, which in turn result in higher performance gain.

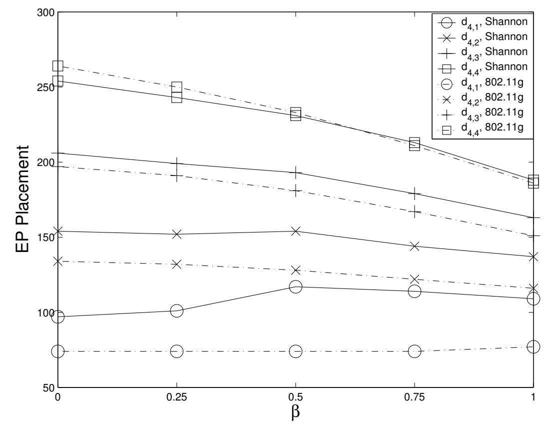

Figure 8. Optimal placement of 4 EPs with respect to different proportion of downlink data.

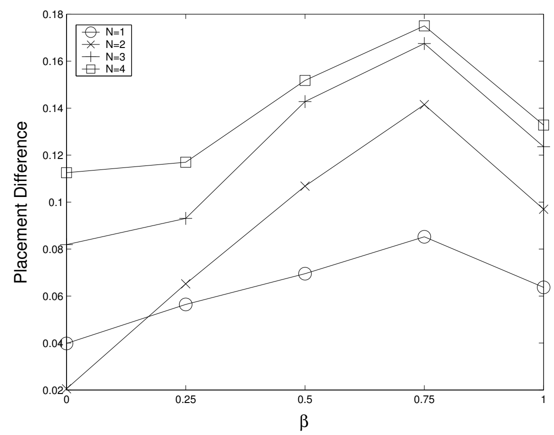

Figure 9. Average placement difference between the two channel models with respect to different proportion of downlink data.

From Fig. 8, the optimally placed EPs are more spread out and further away from the AP when the proportion of downlink data, β, is low. This is because the MHs are less powerful, and when they have more to transmit, MHs that are located far away from the AP need more help. Therefore, to minimize the expected packet transaction time, the EPs should be placed further away from the AP. However, by using the 802.11g model, the optimal placements of the EPs do not change significantly when the traffic characteristic changes slightly. This suggests that even the traffic varies slightly with time, the EPs found by the proposed algorithm can always produce close to optimal results.

From Fig.9, we observed that the difference of optimal placements obtained by the two channel models is small when the proportion of downlink data is small. As in the previous subsection, in most cases, the deviation between the two models increases when the number of EPs increases.

6. Conclusions

In this work, we have investigated the optimal placement of wireless EPs to maximize the capacity of a rectilineal WLAN. An efficient optimal EP placement algorithm is proposed. Different channel models can be used in the proposed algorithm as long as certain convexity conditions are satisfied. In this work, the ideal Shannon point-to-point capacity bound and the IEEE 802.11g physical layer model with Rayleigh fading are considered. From the numerical analysis, we have showed that in most cases, by using a few optimally placed EPs, the network capacity can be significantly improved. Moreover, for different channel models and network environment, the effects of the AP/EP power to MH power ratio, network roll off factor, proportion of downlink data, and number of available EPs, with respect to the optimal EP placement and performance gain are quantified. Given a set of network parameters, the proposed algorithm can be used by network designers to compute the optimal placement of EPs and justify the tradeoff between additional hardware cost and system performance gain.

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