Effect of Relaying on Capacity Improvement in Wireless Local Area Networks

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***Abstract*— Wireless relay nodes can improve the capacity of wireless networks. In this work, we integrate wireless relay nodes to the infrastructure of a Wireless Local Area Network (WLAN). In particular, we investigate the effect of different relay strategies and optimal utilization of a fixed number of immobile relay nodes, which maximizes the expected throughput capacity of the network. We study how the number of relay nodes, the range of users, transmission power, path loss exponent, and traffic characteristics affect the optimal relay node placement and expected throughput capacity of the network. Our results show that a time-division relay strategy can far outperform a receive-and-retransmit relay strategy. Furthermore, for a wide range of system parameters, optimally placed relay nodes can significantly increase the network expected throughput capacity.**

I. Introduction

In the near future, wireless access to the Internet is expected to become a necessity. Wireless Local Area Network (WLAN) standards such as IEEE 802.11 and HiperLAN/2 provide wireless broadband data access for mobile Internet users. Because of WLAN's low cost and high bandwidth, products that support these standards and public hot spots have become increasingly popular, with many analysts envisioning a doubling in sales every year for the next five years.

Currently, the most commonly implemented WLANs in North America is based on the IEEE 802.11b standard, which is capable of supporting bit rates up to 11Mb/s. Two more recent standards, IEEE 802.11a and 802.11g, which are primarily based on Orthogonal Frequency Division Multiplexing (OFDM), are capable of supporting up to 54Mb/s. The increase in bit rate is 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. The main objective of this work is to increase the average bit rate between the access point (AP) and the mobile host (MH) for non-real time applications.

One technique to improve network capacity is to use an intermediate relay node (RN) to boost the power of a wireless signal. Based on current commercially available equipment such as Extension Points (e.g., D-Link DWL-800AP+ and Linksys WRE54G), a relay node can perform relay function analogous to a signal regenerator in the wired network. However, with more advanced signal processing techniques such as simultaneous packet reception, the capacity of an infrastructure wireless relay network can further improve.

In this work, we focus on using immobile wireless relay nodes to relay traffic in a single access point WLAN. Innovative techniques to use immobile relay nodes have been proposed in the past, such as load balancing [1] and adaptive scheduling [2], to improve the capacity of wireless networks. However, the problem of how to place the relay nodes such that the throughput capacity of the network is optimized has not been studied. In this work, we explore how the different relay strategies and relay node placement affect the performance of WLANs.

The rest of this paper is organized as follows. In Section II, we review the related work in multihop wireless networks. In Section III, we explain the system model that is used in this work. In Section IV the optimal placement of wireless relay nodes in a two dimensional single AP scenario is discussed. In Section V, we discuss the effect of different system parameters on the optimal placement of the RNs. Finally, in Section VI, we conclude.

II. Related Work

During the past several years, wireless multihop networking has attracted increasing research interest. Inspired by recent advances in ad hoc networking [3], the concept of using peer mobile hosts to relay data has been explored in the context of cellular networks. In [4], the concept of multihop cellular network was introduced. The authors found that by using peer mobile hosts to relay data to the base station can improve network performance when compared to the traditional single hop cellular network. Based on the concept of using mobile hosts to relay traffic, routing protocols which emphasize on energy saving and capacity maximization have been proposed in [5] and [6] respectively. In a more recent work, the problem of joint routing, link scheduling and power control in such multihop networks was investigated [7]. Moreover, issues about frequency assignment and frequency recycling in such multihop networks have been addressed in [8].

The concept of using immobile relay nodes to relay traffic has received less attention. Immobile relay nodes have several advantages when compare to mobile relay nodes. First, because of their fixed location, it is reasonable to assume that they have access to power supply (or are equipped with a high-capacity battery). Consequently, unlike other systems that use mobile hosts as relay nodes, energy is no longer a constraint. Second, since the distance between an AP and a fixed relay node is relatively static, the link between them should be relatively stable. Some other benefits of fixed relay nodes can be found in [9] and [10].

The concept of using immobile relay node to relay traffic has been discussed in several other contexts. In [1], the $iCAR$ architecture for cellular networks was introduced. $iCAR$ uses relay nodes to relay traffic from a congested cell to the less congested neighbor cells. The authors showed that the relays balance the traffic among cells and in turn improve the system performance.

In [11] and [12], the authors proposed to use extension points to perform relaying in the HiperLAN/2 and IEEE 802.11 systems respectively. Their objective was to increase the coverage area provided by a single AP. The authors of [11] proposed a new MAC frame/sub-frame structure for a HiperLAN/2 system that takes the relay nodes into account. In [9], the authors evaluated this new MAC frame/sub-frame structure in a HiperLAN/2 system with Extension Points. 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.

The works cited above provide solid evidence about the potential benefit of relay in wireless network. In this work, we consider multiple relay strategies and the optimal placement of relay nodes in a two-dimensional WLAN.

III. System Model

A. Communication Protocol

In this work, a system model similar to 802.11 PCF is used. An AP is connected to the internet, and MHs that are within the coverage area of this AP access the internet via this AP. Before a MH can access an AP, it has to be registered, and the AP will maintain a polling-list of all the MHs that are in its coverage area. During each polling period, the AP will poll and send data (if any) to each MH in its polling-list one by one. In other words, at any given time, only one MH is communicating with the AP.

A MH transmits only after it has been polled. When the AP transmits to a MH, it will select the most suitable relay node to assist its transmission (or directly transmit to the MH, if none of the relay nodes can be used to improve the overall transmission rate), while the reverse is performed when the MH transmits to the AP. We assume that the relay decisions are made by the AP, and the relay commands are convey to the relay nodes and MHs in the polling messages. In this work, we assume that the AP always makes the correct decision. In the following subsections, we will describe the path loss and the relay channel models.

B. Free Space Propagation

In this paper, the following free space propagation path loss model is used [13].

$$P_a d_a^\alpha = P_b d_b^\alpha \quad , \qquad (1)$$

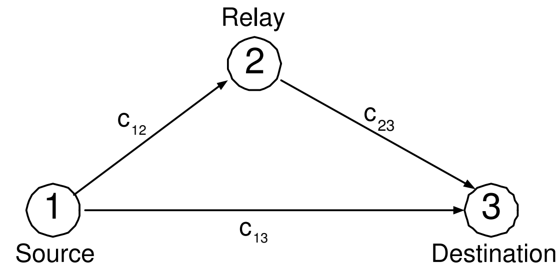

Fig. 1. The relay channel.

where P_a and P_b are the signal power measured at d_a and d_b meters away from the transmitter respectively, and α is a positive constant representing the path loss roll off factor. For simplicity, we set d_a to 1 meter, and thus P_a is the *reference* signal power measured at 1 meter away from the transmitter. Equation (1) is simplified to

$$P_b = \frac{P_a}{d_b^\alpha} \quad . \qquad (2)$$

C. Relay Channel Capacities

Consider the channel in Fig. 1. The source, node 1, is intended to communicate with the destination, node 3. The relay node, node 2, is designed to help the communication between the source and destination. The source and relay transmitters are subject to power constraints of P_1 and P_2 respectively, and c_{12}, c_{13}, and c_{23} are the signal amplitude losses. This relay channel was first studied in [14], and later considered by [15].

If all the receivers are subject to Additive White Gaussian Noise (AWGN) with zero mean and unit variance, the relay channel capacity is

$$\begin{aligned} C &= C_r(P_1, P_2, c_{12}^2, c_{13}^2, c_{23}^2) \\ &= \max_{0\le\beta\le1} \min \Big\{ \frac{1}{2}\log(1 + (1-\beta)P_1(c_{12}^2 + c_{13}^2)), \\ &\quad \frac{1}{2}\log(1 + c_{13}^2 P_1 + c_{23}^2 P_2 + 2\sqrt{\beta c_{13}^2 c_{23}^2 P_1 P_2}) \Big\} . \end{aligned} \qquad (3)$$

The above relay channel capacity is obtained based on two assumptions. First, the destination receiver can decode signals from different transmitters using the same channel simultaneously. Second, the relay node can transmit and receive in the same channel at the same time. For wireless channel, the latter assumption is not realistic. As a result, the Time Division (TD) relay channel, which was studied in [16] and [17], was introduced. In a TD relay channel, a node cannot transmit and receive signal in the same channel simultaneously. In other words, the relay node operates in two modes: receive mode and transmit mode. In the receive mode, the source sends data to both the relay and the destination, the relay node receives and decodes the signal. In the transmit mode, both the source and relay node transmit to the destination, when the relay node retransmit the data that it has received. The achievable capacity of a TD relay channel is

$$
\begin{aligned}
C &= C_{td}(P_1, P_2, c_{12}^2, c_{13}^2, c_{23}^2) \\
&= \frac{1}{2} \max_{0 \le \beta, t \le 1} \min \{ t \log(1 + c_{12}^2 P_1) + \\
&\quad (1-t) \log(1 + (1-\beta) c_{13}^2 P_1), \quad t \log(1 + c_{13}^2 P_1) + \\
&\quad (1-t) \log(1 + c_{13}^2 P_1 + c_{23}^2 P_2 + 2\sqrt{\beta c_{13}^2 c_{23}^2 P_1 P_2} \Big\} .
\end{aligned} \tag{4}
$$

Even though the TD relay channel model is more realistic than the one calculated by (3), the current state-of-the-art wireless relay nodes, such as extension points, are not able to receive multiple signals from the same channel simultaneously. By using the current technology, if the source decides to send a packet to the destination via a relay node, the source will first transmit the packet to the relay node. After the relay has received the entire packet, the relay node will retransmit this packet to the destination. If the relay node is used, the source will not communicate with the destination directly. In this paper, we name the above a Receive-and-Retransmit (RR) relay channel. Since the achievable channel capacity of a point to point channel is given by [18]

$$C_{pp} = \frac{1}{2} \log(1 + P_r), \tag{5}$$

where P_r is the received signal power, the capacity of the channel when the relay is used is

$$\left[\frac{1}{\frac{1}{2}\log(1 + c_{12}^2 P_1)} + \frac{1}{\frac{1}{2}\log(1 + c_{23}^2 P_2)} \right]^{-1} . \tag{6}$$

Unlike in the TD relay strategy, where the source always uses the relay to transmit to the destination, in the RR relay strategy, the relay may or may not be beneficial. In other words, if the relay node is used, the resulting capacity may be lower than the original point to point capacity between the source and destination. Thus, the source should use the relay only if it is beneficial. The resulting capacity of a RR relay channel is

$$
\begin{aligned}
C &= C_{rr}(P_1, P_2, c_{12}^2, c_{13}^2, c_{23}^2) \\
&= \max \left\{ \left[\frac{1}{\frac{1}{2}\log(1 + c_{12}^2 P_1)} + \frac{1}{\frac{1}{2}\log(1 + c_{23}^2 P_2)} \right]^{-1} \right. \\
&\quad \left. \frac{1}{2} \log(1 + c_{13}^2 P_1) \right\} .
\end{aligned} \tag{7}
$$

In this work, we investigate how different relay strategies affect the optimal placement of the relay nodes, which maximizes the expected throughput capacity of the network. Since we do not expect a wireless relay node has the ability to transmit and receive in the same channel simultaneously in the near future, we will only investigate the placement problem by using the TD relay channel and the RR relay channel.

IV. Throughput Capacity and Optimal Relay Node Placement

In the simplest scenario, as depicted by Fig 2, we have a MH, a RN, an AP, and the following system parameters.

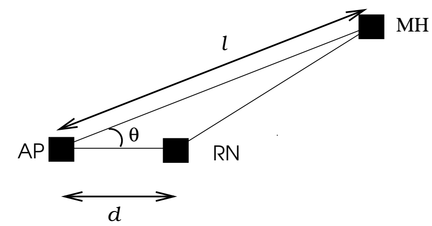

Fig. 2. Positions of AP, RN, and MH.

- β = proportion of downlink data. (i.e. $1-\beta$ is the proportion of uplink data, where $0 \le \beta \le 1$.)
- α = path loss roll off factor.
- P_{ar} = reference power of AP or RN.
- P_m = reference power of MH. ($P_m \le P_{ar}$)
- d = distance between AP and RN.
- l = distance between AP and MH. ($d < l$)
- $\theta = \angle$ MH-AP-RN

Since the AP and RN are immobile, it is reasonable to assume that they have access to power supply or are equipped with a high capacity battery. Consequently, in our system model, it is reasonable to assume that $P_m \le P_{ar}$.

We assume that none of the nodes are able to receive and transmit in the same channel simultaneously. Thus, downlink and uplink are time multiplexed. Suppose there are x bits that the AP and MH wish to communicate (i.e., $x\beta$ bits of downlink data and $(1-\beta)x$ bits of uplink data). If the relay node is absent, the time required to complete the data transaction is

$$T_{direct}(l) = \frac{x\beta}{\frac{1}{2}\log(1 + \frac{P_{ar}}{l^\alpha N})} + \frac{x(1-\beta)}{\frac{1}{2}\log(1 + \frac{P_m}{l^\alpha N})} . \tag{8}$$

Hence, we define the *throughput capacity* of this MH as

$$
\begin{aligned}
C_{direct}(l) &= \frac{x}{T_{direct}(l)} \\
&= \left[\frac{\beta}{\frac{1}{2}\log(1 + \frac{P_{ar}}{l^\alpha N})} + \frac{(1-\beta)}{\frac{1}{2}\log(1 + \frac{P_m}{l^\alpha N})} \right]^{-1} .
\end{aligned} \tag{9}
$$

Now, suppose the relay node is used (if beneficial) to enhance the transmission. Again, we assume there are x bits that the AP and the MH wish to communicate. The time required to complete the transaction is

$$
\begin{aligned}
T_{relay}(l, d, \theta) &= \frac{x(1-\beta)}{C(P_m, P_{ar}, \frac{1}{e^\alpha}, \frac{1}{l^\alpha}, \frac{1}{d^\alpha})} + \\
&\quad \frac{x\beta}{C(P_{ar}, P_{ar}, \frac{1}{d^\alpha}, \frac{1}{l^\alpha}, \frac{1}{e^\alpha})} ,
\end{aligned} \tag{10}
$$

where $e = |l^2 + d^2 - 2ld\cos\theta|^{\frac{1}{2}}$, and C can be either C_{rr} or C_{td}. Thus, the throughput capacity of this MH is

$$
\begin{aligned}
C_{relay}(l, d, \theta) = \Bigg[&\frac{(1-\beta)}{C(P_m, P_{ar}, \frac{1}{e^\alpha}, \frac{1}{l^\alpha}, \frac{1}{d^\alpha})} + \\
&\frac{\beta}{C(P_{ar}, P_{ar}, \frac{1}{d^\alpha}, \frac{1}{l^\alpha}, \frac{1}{e^\alpha})} \Bigg]^{-1} .
\end{aligned} \tag{11}
$$

In this work, we consider a two-dimensional model as shown in Fig. 3. In this scenario, we are given a number

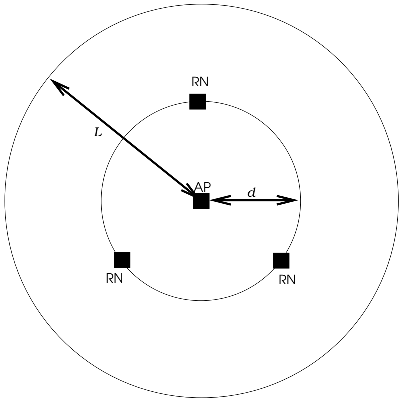

Fig. 3. Network Configuration.

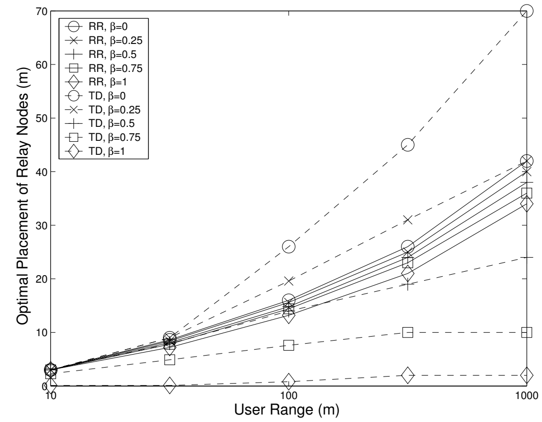

Fig. 4. Effect of user range and proportion of downlink data, for $\frac{P_{ar}}{N} = 40$, $\frac{P_m}{N} = 20$, $\alpha = 2$, and $n = 16$.

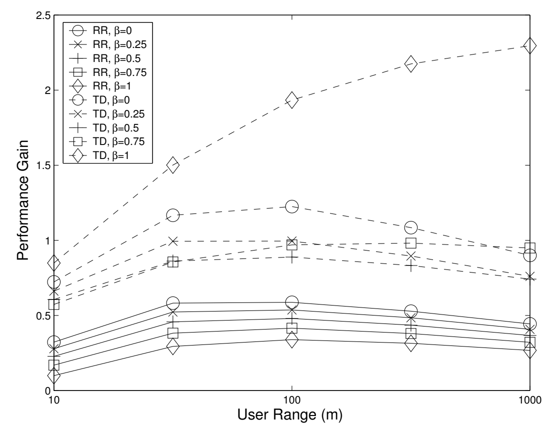

Fig. 5. Effect of user range and proportion of downlink data, for $\frac{P_{ar}}{N} = 40$, $\frac{P_m}{N} = 20$, $\alpha = 2$, and $n = 16$.

of relay nodes (in this example 3). These relay nodes are placed uniformly around the AP. Each relay node is placed d meters away from the AP. The MHs are uniformly distributed on the circle with radius L centered at the AP. We first evaluate the expected throughput capacity of the network without relay nodes. The throughput capacity of each MH located l meters away from the AP is given by (9). Thus the expected throughput capacity of the network is

$$\overline{C_{direct}} = \int_0^{2\pi} \int_{0+\epsilon}^{L} \frac{l}{\pi L^2} C_{direct}(l) dl d\theta \quad , \qquad (12)$$

where $\epsilon > 0$ is small.

Now, let us evaluate the network capacity with the help of relay nodes which are placed uniformly around the AP. Consider the mobile host in Fig. 2. The throughput capacity of this MH is given by (11). Thus, the the expected throughput capacity is

$$\overline{C_{relay}(d)} = \frac{n}{L^2\pi} \int_{\frac{-\pi}{n}}^{\frac{\pi}{n}} \int_{0+\epsilon}^{L} l C_{relay}(l, d, \theta) dl d\theta \ , \qquad (13)$$

where $n > 1$ is the number of available relay nodes[1]. By using (13), the optimal relay node placement problem can be casted as the following optimization problem

$$\text{Objective:} \quad \max_{d} \quad \overline{C_{relay}(d)} \qquad (14)$$

$$s.t. \quad 0 < d < L \quad .$$

In this study, the desired optimal distance d^* is solved numerically for each of the relay strategies. In the next section, we discuss some observations obtained from the numerical results.

V. Numerical Analysis

The system that we investigate has six parameters: reference power of the AP and RN over noise ratio (P_{ar}/N), reference power of MH over noise ratio (P_m/N), roll off factor (α), proportion of downlink data (β), user range (L), and number of relay nodes (n). For each relay strategy and a particular set of system parameters, there is an optimal placement of the relay nodes, d^*, and the corresponding capacity, $\overline{C_{relay}(d^*)}$. The performance gain is defined as

$$Gain = \frac{\overline{C_{relay}(d^*)} - \overline{C_{direct}}}{\overline{C_{direct}}} \quad , \qquad (15)$$

In the following, the relationship among these six parameters with respect to the optimal relay node placement, performance gain, and relay strategy will be discussed.

In Fig. 4 and Fig. 5, we study the effect of user range and proportion of downlink data in the network. The four network parameters P_{ar}/N, P_m/N, α and n are fixed. From Fig. 4, for both types of relay strategies, the optimal relay node position moves further away from the AP as the user range increases. This is because a large user range means that more MHs are located far away from the AP. The expected throughput capacity of the network is higher if the relay nodes are located closer to the far away MHs. On the other hand, as the proportion of downlink data decreases, the optimal relay node position moves further away from the AP. This is because the relay nodes should be placed closer to the transmitters that has more data to send in order to achieve optimal performance. Even though the same trends were observed for both types of

[1]Note that (12) and (13) represent per-user throughput capacities assuming the user has a uniform mobility pattern such that it remains at any position with an equal amount of time.

relay strategies, the effect of the user range and proportion of downlink data on the optimal placement of relay nodes is larger when the TD relay strategy is used.

From Fig. 5, we found that for the RR relay channel case, the performance gain is low when the user range is either small or large. This is because when the user range is small, most MH can achieve high capacity without using the relay nodes. In the other extreme case, when the user range is large, most MH can only achieve a small capacity improvement with the help of relay nodes. This explains why the performance gain is small in these two extreme cases. For the TD relay channel case, the same observation was found for small β. However, by using the same argument for the RR relay channel, when β is large, the same observation is expected when the user range increases further. From the same figure, for the RR relay channel, the performance gain increases as the proportion of uplink data, $(1-\beta)$, increases. This is because the MH's transmitter has less power when compared to the AP and RNs. As the amount of data need to be transmitted by the MH's transmitter increases, the beneficial effect of the relay nodes becomes more and more significant. From our results, when the user range is 100m, if the MHs only have uplink data to send, the performance gain of 59% is achieved, while if the MHs only have downlink data to send, the performance gain is only 34%. For the TD relay channel, the results are more interesting. It has the same trend as the RR relay channel when the proportion of downlink data, β, is small. However, when β is large, the performance gain increases as β increases. When there is only downlink data, the performance gain can be more than 200%. From Fig. 4, we observed that when β is large, the optimal relay node position is very close to the AP. In these cases, since the proportion of uplink data is small, it is more beneficial to improve the downlink bit rate. Since the relay nodes are in close proximity with the AP, in the receive mode, the AP can transfer a large amount of information to the relay node in a very short amount of time. In the transmit mode, both the AP and RN transmit to the MH. This is equivalent to a multiple access channel. In effect, the signal power received by the mobile host is effectively doubled. This explains why the performance gain is high when the majority of the data is downlink data.

In Fig. 6 and Fig. 7, we study the effect of the mobile to AP/RN power ratio and the AP/RN power to noise ratio in the network. The four network parameters α, β, L, and n, are fixed. From Fig. 6, the optimal relay node position moves away from the AP as the $\frac{P_m}{P_{ar}}$ ratio decreases. This is because a MH needs relatively more help when its transmitter power is low. Thus, in order to optimize the network expected throughput capacity, the relay nodes should be placed closer to the majority of the MHs. From the same figure, the optimal relay node position moves away from the AP as the power of AP, RNs and MHs increase by the same percentages. This is because when the power of transmitters increases, the MHs close to the AP can achieve high enough bit rate such that the effect of a relay node between these MHs and the AP becomes less significant. In order to optimize the network expected throughput capacity, it is logical to move the relay nodes further away from the AP so that the relay nodes can assist the MHs far away from the AP.

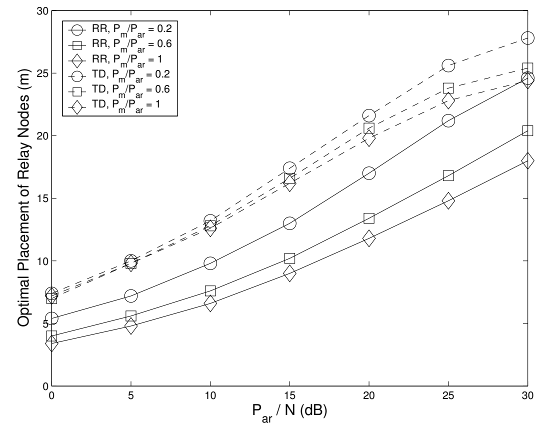

Fig. 6. Effect of the mobile to AP/RN power ratio and the AP/RN power to noise ratio, for $\alpha = 2$, $\beta = 0$, $L = 50$, and $n = 16$.

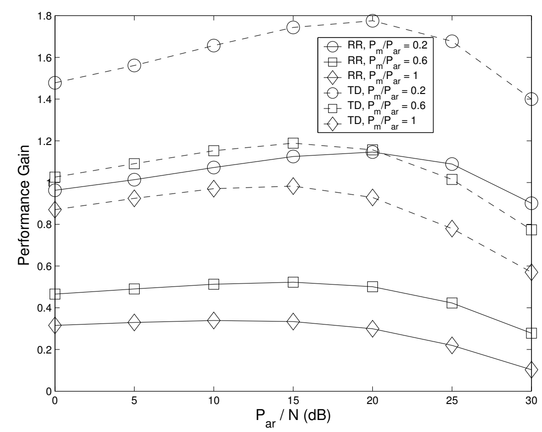

Fig. 7. Effect of the mobile to AP/RN power ratio and the AP/RN power to noise ratio, for $\alpha = 2$, $\beta = 0$, $L = 50$, and $n = 16$.

From Fig. 7, the performance gain increases as the $\frac{P_m}{P_{ar}}$ ratio decreases. This is because when the MH's transmitter power is low, the effect of the relay node becomes more significant. From the same figure, when the power of the transmitters are high, the performance gain is a decreasing function of $\frac{P_{ar}}{N}$. This is because a higher power transmitter can achieve a higher bit rate; in effect, this decreases the utility of the relay nodes.

In Fig. 8 and Fig. 9, we study the effect of the roll off factor, α, and the number of relay nodes, n, in the network. The four network parameters P_{ar}/N, P_m/N, L, and β are fixed. From Fig. 8, for both types of channels, as the roll off factor increases, the optimal relay node location moves closer and closer to the AP. The roll off factor determines how fast the signal decades when it travel through a distance. As the roll of factor increases, it is harder and harder for the relay node to help distant MHs. Thus, it is more beneficial to help MHs that are relatively closer to the AP. From the same figure, by using the TD relay strategy in small attenuation environments,

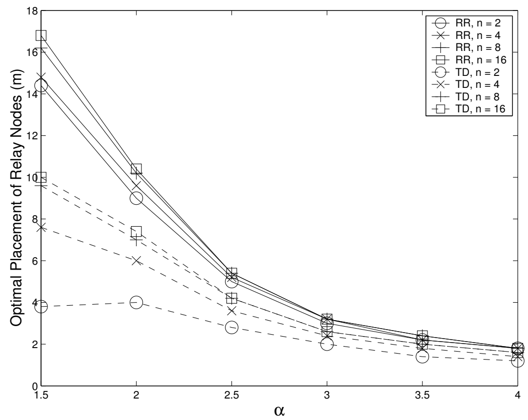

Fig. 8. Effect of roll off factor (α) and the number of relay nodes, for $\frac{P_{ar}}{N} = 40$, $\frac{P_m}{N} = 20$, $\beta = 0.7$, and $L = 50$.

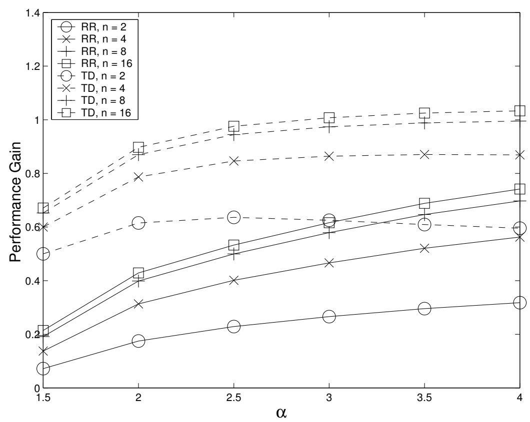

Fig. 9. Effect of roll off factor (α) and the number of relay nodes, for $\frac{P_{ar}}{N} = 40$, $\frac{P_m}{N} = 20$, $\beta = 0.7$, and $L = 50$.

i.e., small α, the effect of the number of available relay nodes on their optimal placement is large when compared to that of the RR relay strategy. From Fig. 9, for both types of relay strategies, the performance gain increases as the roll off factor increases. This is because as the signal decades faster, the beneficial effect of a relay node that boost the throughput becomes more and more significant. The beneficial effect of the relay nodes in high attenuation environments is also observed in the empirical study in [9].

VI. Conclusions

In this work, we have investigated the optimal placement of wireless relay nodes to maximize the expected throughput capacity of a WLAN under different relay strategies. We have showed that in most cases, by using a few relay nodes optimally placed around a single AP, the expected throughput capacity of the network can be improved significantly.

Our results show that a time-division relay strategy can far outperform a receive-and-retransmit relay strategy. In terms of optimal relay node placement, both relay strategies have similar trends with respect to different system parameters. The optimal placement of the relay nodes are close to the AP as the proportion of downlink data, P_m/P_{ar} ratio, network roll off factor increase, and as the user range, transmitter power of the AP and RN, and the number of relay nodes decrease. In terms of performance gain, similar trends have been observed for both types of relay strategies except for different proportion of downlink data. For the TD relay strategy, the performance gain can be higher than 200% when β is large, while for the RR relay strategy, the performance gain always decreases as β increases. Furthermore, our analytical result has confirmed the previous empirical observations [9][11] on the diminishing return of large number of relay nodes and on the beneficial effect of relay nodes in high attenuation environments.

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