On the advantages of multi-hop extensions to the IEEE 802.11 infrastructure mode

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Abstract— **IEEE 802.11 specifies two modes of operation, an infrastructure mode where nodes communicate to/through an access point, and an ad-hoc mode, where nodes communicate with each other directly. Neither mode supports multiple hop transmissions between these nodes. In this paper we present two advantages in extending 802.11 MAC to support multiple hops in the infrastructure mode. One advantage is higher available bandwidth in a multi-rate 802.11 network. IEEE 802.11 allows hosts to select different transmission rates based on the quality of the signal received by the host. Based on performance results both from analytical modeling and simulations[1], we demonstrate that the total available bandwidth can be improved by using multiple hops instead of reducing the transmission rates of nodes. We present the results in terms of both the increase in total throughput of the network and the available throughput for the forwarding node. The second advantage presented is that by using multi-hop transmissions, the power of transmission at the edges of 802.11 cells can be reduced resulting in lower interference with nodes at the edges of other 802.11 cells. This leads to a more uniform coverage, with increased throughput experienced by nodes at the cell edges.**

Keywords— **IEEE 802.11, MAC, Wireless LANs, Link adaptation, signal-to-interference ratio, multi-hop forwarding.**

I. Introduction

THE IEEE 802.11 MAC specification defines two modes of operation: infrastructure and ad-hoc mode. The standard does not define support for multi-hop transmissions in either mode. There is a large body of research considering multi-hop networking using the 802.11 MAC. With respect to the infrastructure mode, multi-hop transmissions have been shown to increase the range of the coverage area of a single access point. Providing such extensions has been considered both as a routing problem [11][13] and as a layer-2 bridging [8] problem. In this paper, we discuss two other significant advantages of using multi-hop transmission in 802.11 infrastructure mode. One advantage relates to the multiple rates supported by the 802.11 standard and the other to the signal-to-interference ratio between proximal cells using the same channel leading to more uniform coverage in terms of per node throughput within the cell.

Using link adaptation schemes to select the appropriate transmission rate is the preferred method to increase throughput of IEEE 802.11 wireless LAN under interference and signal fading conditions. In this paper, we study the applicability of multi-hop forwarding to address the signal quality problem. Instead of reducing the transmission rate at a node that is far from the access point, we consider utilizing an intermediate node to forward traffic while keeping all nodes at the highest possible transmission rate. By utilizing an intermediate forwarding node to reach the access point, the transmission power can also be reduced because of the reduced distance between the two nodes. Such a reduction in transmission power will reduce interference in proximal 802.11 cells that are using the same channel. We present this reduction in signal-to-interference ratio and the resulting improvement in the coverage within a 802.11 cell as the second advantage in utilizing multi-hop transmission in the 802.11 infrastructure mode. This second advantage is important in a dense coverage setting like campuses where uniform coverage is desirable.

It is important to note that there is a trade off between these two advantages, as reducing power may affect the transmission rate between the edge node and the forwarding intermediary.

A. Related work

[4] notes that a single slow host negatively impacts the throughput available for all the nodes in the network. This

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anomaly is attributed in part to the long-term fairness inherent in the design of IEEE 802.11 MAC. Long term fairness guarantees that the probability of channel access is the same ($\frac{1}{N}$, where N is the number of nodes) for all the nodes irrespective of their transmission rates. When a slow node captures the channel, it will hold the channel longer to complete its transmission than a faster node would for a same size frame transmission. This leads to a reduced number of transmission attempts by every node in any given time interval and hence the available throughput for every node (including the fast ones) are negatively impacted. The analysis presented in [4] considers only one slow node in the network whereas we consider multiple slow nodes at different transmission rates. We also present multi-hopping as a means to ameliorate this problem. Also, a variety of link adaptation schemes have been proposed [6] [14] [16] to estimate the best bit-rate a wireless node should use for transmission. To our knowledge the relationship between multi-hop transmissions and interference has not been discussed in the literature.

II. Analytical Model

In this section, we derive an expression for the total saturation throughput of each node (S_{node}) in a multi-rate environment in terms of the number of nodes at each possible transmission rate.

A. Maximum number of attempted transmissions

Let the transmission time for packet at transmission rate X Mbps be represented by T_X.

$T_X = T_{Overhead} + \frac{l}{X}$

where $T_{Overhead}$ is the sum of $PLCP\_OVERHEAD$, $DIFS$, CW_TIME, $SIFS$, and ACK_TIME, and l is length of the packet given in bits. For the rest of this paper we assume fixed $T_{overhead}$ based on the values shown in Table I. The contention time CW_TIME is calculated using CW_{Avg}, to be determined from the equation (2), as follows, $CW\_TIME = \frac{CW_{Avg}}{2} * MINI\_SLOT\_TIME$.

Because of the long term channel access fairness guaranteed by the 802.11 MAC, and assuming all nodes have a backlog of frames to transmit, each of the N nodes in the network will have an equal expected number of frame transmissions in a given amount of time (T in μs). The time taken for transmission by each of the nodes in the network depends on the their respective transmission rates.

Let f_X stand for the fraction of nodes that transmit at the rate X Mbps, such that $f_{11} + f_{5.5} + f_2 + f_1 = 1$. Let T_X (in μs) be the time needed to transmit a packet at X Mbps, where we assume that all nodes transmit equal size packets. The total number of transmissions attempted (N_T) during the total time has the following form:

TABLE I

802.11 MAC constants

Constants	Values
SIFS	10 μs
DIFS	50 μs
ACK TIME	112 μs
EIFS	364 μs
ACK Timeout	314 μs
PLCP OVERHEAD	281 μs
MINI_SLOT_TIME	20 μs

$$\lim_{T\to\infty} N_T \to \frac{T}{\sum_X f_X T_X} \quad (1)$$

B. Probability of collision

[7] derives a nonlinear system of two equations in two unknowns τ and p, representing the probability of transmission and probability of collision, respectively. It is assumed that at each transmission attempt, regardless of the number of retransmissions suffered, each packet collides with constant and independent probability p. In this section we derive an approximate expression for p based on the minimum contention window CW_{min}, m^* and the number of nodes in the network, where m^* is given by the equation $CW_{max} = 2^{m^*} CW_{min}$; CW_{max} is the maximum contention window.

Let the probability of collision when all the nodes are selecting a random interval in the window size $2^m CW_{min}$ be denoted by P_m, $m = 0, 1...m^*$.

As described in [4], P_m can be expressed as

$$P_m = 1 - (1 - 1/(2^m * CW_{min}))^{N-1}$$

.

The average window size (CW_{Avg}) can be approximated by (assuming that all nodes have the same m), $CW_{Avg} =$

$$(\sum_{i=0}^{m^*-1} \Pi_{j=0}^{i-1} P_j (1 - Pi) 2^i + (\Pi_{j=0}^{m^*} P_j) 2^{m^*}) CW_{min} \quad (2)$$

where $\Pi_j^k = 1$ if $j > k$. This expression calculates the average contention window size by a summation of the product of the probability that the contention window is $2^i CW_{min}$ for $i = 1..m^*$ and the window size. For example, the probability that the contention window is $2^2 CW_{min}$ for a particular transmission can be expressed as $P_0 P_1 (1 - P_2)$.

Finally, we can then approximate the probability of collision as

$$p = 1 - (1 - 1/CW_{Avg})^{N-1} \tag{3}$$

C. Throughput of the network

From (1), the total number of *successful* transmissions N_s, over a period of time T, is given by

$$\lim_{T\to\infty} N_S = \frac{T * (1-p)}{\sum_X f_X T_X} \tag{4}$$

where p is the probability of collision.
Total saturation throughput S in bits per second of the network

$$S = \lim_{T\to\infty} \frac{N_S * l}{T} = \frac{(1-p) * l}{\sum_X f_X T_X}$$

and the total saturation throughput available for each node (S_{node}) in the network is

$$S_{node} = S/N \tag{5}$$

TABLE II
AVERAGE THROUGHPUT PER NODE

	Case 1	Case 2	Case 4	Case 5
# Nodes	5	5	16	16
# @ 11 Mbps	4	3	10	12
# @ 2 Mbps	1	2	0	0
# @ 1 Mbps	0	0	6	4
(Anal) Kbps	651	501	83	105
(Simul)Kbps	652	489	83	106

III. SIMULATION RESULTS

We simulated a 24 node 802.11 network using the OPNET Modeler [9] with all the high speed nodes transmitting at 11 Mbps. The simulation was run multiple times with the number of slow nodes (transmitting at 1 Mbps) ranging from 1 through 11 and the average throughput per node was compiled. Fig 1 shows the result along with the value calculated using equation (5). It can be seen from Fig.1 that the average throughput achieved by each node (even the nodes that can transmit at the higher rate of 11 Mbps) drops as the number of slow nodes (1 Mbps) in the network increases. This is expected from the long term fairness guaranteed by the MAC design. The average throughput per node using simulation and analysis is also presented for various configurations in the Table II. There appears to be a good agreement between the analytical and simulation results.

IV. TWO HOP FORWARDING

Instead of reducing the transmission rate of the nodes farther away from the access point, we considered the possibility of allowing those nodes to use an intermediate node to forward their traffic. In such a scenario, if all the nodes can still transmit at the highest possible rate of 11 Mbps, the total channel throughput will not suffer the performance anomaly demonstrated earlier. But the total useful throughput (sometimes called *goodput*) of data (i.e. the throughput of data received at the access point) will be less than channel throughput because data from the multi-hop source nodes are transmitted twice on the channel before they reach their destination.

V. SIMULATION RESULTS

Again using the 24 node 802.11 network, we simulated a multi-hop forwarding scenario where devices that can only transmit at slower rates to the access point (1 Mbps), communicate with a forwarding node at high speed (11Mbps) and the forwarding nodes in turn transmit the frame to the access point at high speed (11 Mbps). In the following discussion we assume that a forwarding node is only responsible for one slow node, i.e. the number of slow nodes in the network is less than half of the total number of nodes and that each of these slow nodes can reach a fast node at the higher rate of 11 Mbps.

Figure 2 shows the total useful throughput of the network when rate adaptation is used, which implies that the farther nodes have to reduce their transmission rate, and total useful throughput if forwarding is used to keep all the nodes at 11 Mbps. As can be seen from Fig.2 the useful throughput is increased by utilizing high-rate forwarding. Even though the total useful throughput is increased, that may not be enough of an incentive for the forwarding nodes to participate in this scheme. We need to look at what benefit the forwarding node derives by participation. Based on the assumption that the forwarding node will have to support only one other slow node, the amount of its own traffic a forwarding node can send will be half its available channel bandwidth. This is, of course, assuming that the internal traffic scheduling logic shares the available channel bandwidth equally between its own traffic and forwarded traffic.

The line in Figure 3 marked “Bandwidth Improvement-current MAC” shows the bandwidth improvement at the forwarding node when the available channel bandwidth is shared equally between its own traffic and the forwarded traffic, while Figure 4 shows the percentage improvement. In this case, forwarding is beneficial for the forwarding node only if there are at least four slower nodes in the net-

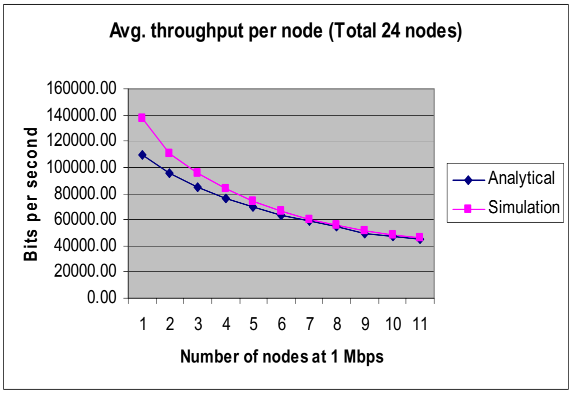

Fig. 1. Average Throughput Per Node - Total 24 nodes

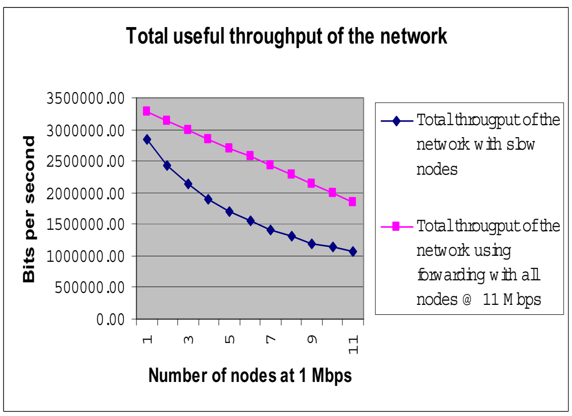

Fig. 2. Total throughput of the network - Total 24 nodes

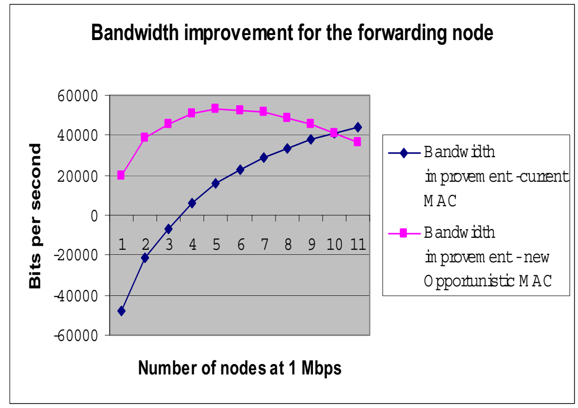

Fig. 3. Bandwidth improvement-forw node -Total 24 nodes

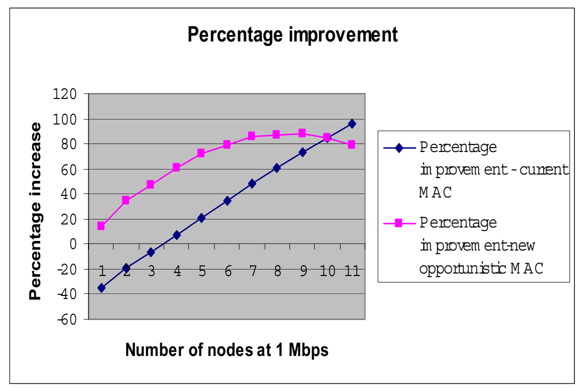

Fig. 4. Percentage improvement-forw node -Total 24 nodes

work and the improvement is over 50% when the number of slow nodes is above seven. Bandwidth improvement here refers to the increase in the number of bits per second transmitted by the forwarding node when two-hop forwarding is used.

Instead of sharing the available channel bandwidth at the forwarding node equally, if the total improved network bandwidth is shared among all the nodes based on a new opportunistic MAC algorithm similar to [5] the resulting improvement for the forwarding node will be increased. [5] proposes a MAC algorithm that guarantee fairness in terms of the channel access time rather than the number of channel access opportunities. Since a slow node will hold the channel for longer for each of its packet transmissions, a faster node is also allowed to hold the channel for an equal amount time with consecutive multiple frame transmissions. A similar mechanism that allows the forwarding nodes to transmit multiple packets will encourage nodes to participate in forwarding. With such an opportunistic scheme, if the total available throughput is shared equally among all the nodes, the forwarding node derives significant benefits even with single slower node in the network (Fig. 3) and the improvement is over 50% (Fig. 4) when the number of slower nodes exceeds three.

VI. Dense Deployment of Access Points for Complete Coverage

The IEEE 802.11b and IEEE 802.11g specifications operate in the 2.4 GHz spectrum and there are 11 channels defined in this spectrum for operation in the US. These channels, numbered 1 to 11, are each 22 MHz wide and spaced at 5 MHz intervals. Hence, there is substantial overlap between adjacent channels. In order to avoid interference between adjacent cells the only three mutually non-overlapping channels that may be used are 1, 6 and 11.

A. Frequency reuse

The *co-channel reuse ratio* is the ratio of the distance between two proximal cells that use the same channel (D)

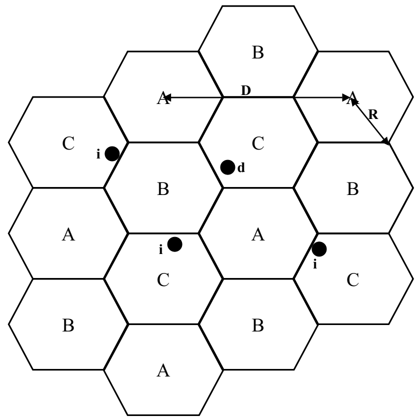

Fig. 5. Frequency reuse - Cell Structure using three channels

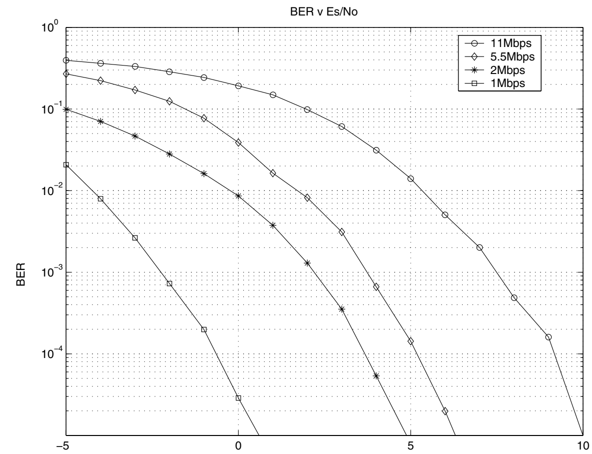

Fig. 6. BER vs SIR

and the radius (R) of each of these cells. Figure 5 shows the cell structure to be used when three channels are available for deployment as is the case in IEEE 802.11b. This co-channel ratio ($\frac{D}{R}$) is derived in [10]:

$$\frac{D}{R} = \sqrt{3N}$$

where N is the number of frequencies in each cluster. In the case of 802.11b, N = 3, and hence the co-channel reuse ratio is also 3. The signal-to-interference (SIR) ratio under ideal conditions, is calculated as $SIR = \frac{3}{2}N^2$. This value is 11.30 dB [10]. This SIR is calculated under the assumptions that all nodes use the same power for transmission and that the average distance between an interferer in one cell and a receiver in another cell is D. For nodes on the edges of these cells, the second assumption may not always hold true. At least three of the six interferers could be at a distance less than D if they are at the nearer edges of their respective cells, as depicted by the device d and its interfering nodes 'i' in figure 5. This proximity with interfering nodes will result in significantly reduced SIR at the edge nodes. In the scenario where nodes can use multiple hops to reach the access point, transmissions by these nodes can use reduced transmission power. Such a reduction in power will be useful in reducing the interference at the edge nodes of proximal cells. The following sections demonstrate this advantage by mapping the data rates available at every point in a cell based on the likely SIR a mobile node will experience at that particular point.

B. Signal-to-Interference ratio vs BER

We restrict our discussion to co-channel interference while assuming a path-loss gradient (α) of 4.

SIR is calculated as follows : $SIR = \frac{Ps}{\sum_j P_j}$

where Ps is the received power of the desired source at the device, while P_j is the received power from interfering node j. In the cell structure shown in Figure 5, it can be seen that there are 6 possible interfering sources from proximal cells. We assume the Rayleigh fading model to simulate the multipath effect on the received signal. The received power from the desired source and the interfering nodes is calculated using the Rayleigh fading model.

In the 802.11b Direct Sequence Spread Spectrum (DSSS) three different modulation schemes are used to support the four different data rates. They are Differential Binary Phase Shift Keying (DBPSK) for 1 Mbps, Differential Quaternary Phase Shift Keying (DQPSK) for 2 Mbps and Complementary Code Keying (CCK) for 5.5 Mbps and 11 Mbps. The control packets and the header of the data packets are always modulated using the DBPSK modulation scheme (at 1 Mbps) and the modulation scheme of the data part is indicated in the PHY header.

Using the expressions for bit error probability from [15], assuming an additive white gaussian noise (AWGN) channel, the performance curves of BER versus SNR for these modulation schemes are shown in Figure 6. Since we have restricted our discussion to co-channel interference, the only source of noise is from interfering nodes in the proximal cells. Based on the performance curves in Figure 6, in order to achieve a BER below 10^{-5}, we need SIR to be above 10 dB for the 11 Mbps data rate, above 7 dB for 5.5 Mbps, above 5 dB for 2 Mbps and above 1 dB for 1 Mbps. These SIR values establish the required thresholds to be met for sustaining the corresponding data rate.

C. Coverage Map

We wrote a simulation program using C, that calculates the SIR for each point in a cell by randomly choosing the locations of six interfering nodes in the six proximal cells sharing the same channel. This caculation was repeated 6000 times for each point in the cell. The data rate that

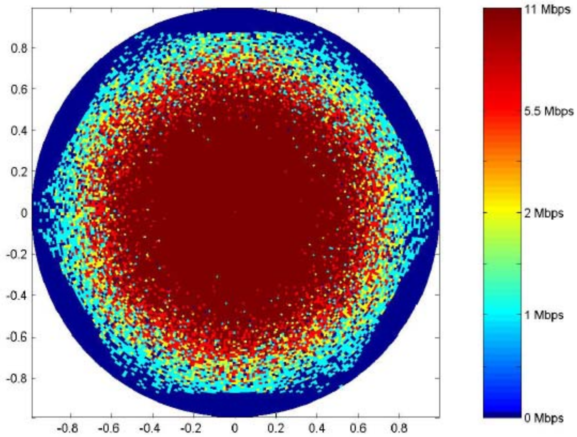

Fig. 7. Downstream Data rate based on SIR (Equal power transmissions)

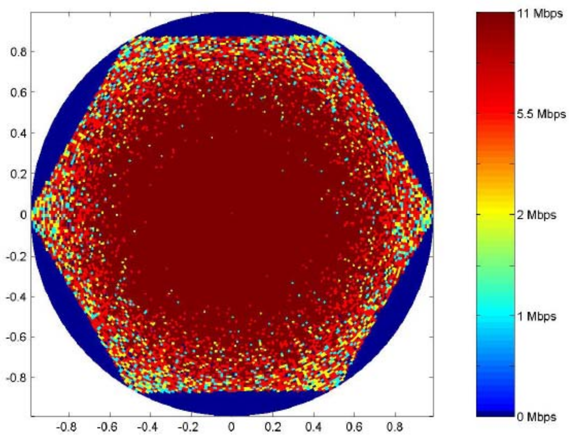

Fig. 8. Upstream Data rate based on SIR (Equal power transmissions)

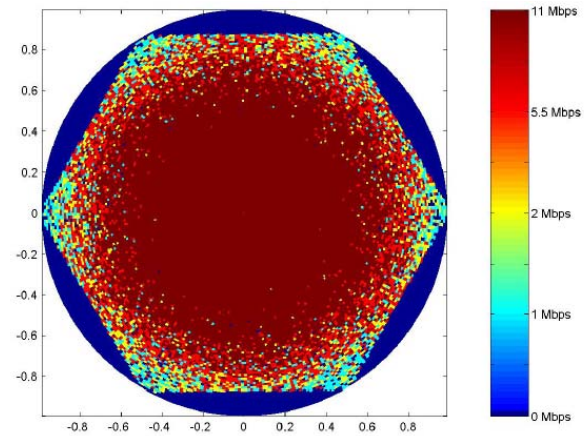

Fig. 9. Downstream Data rate based on SIR with transmission power reduction at edge nodes

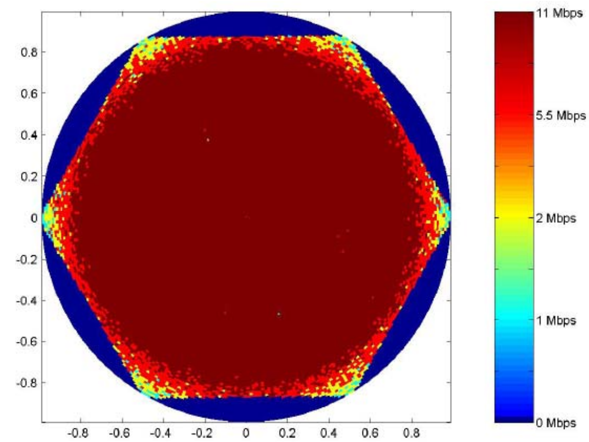

Fig. 10. Upstream data rate based on SIR with transmission power reduction at edge nodes

will be available at that particular point is estimated based on the SIR threshold requirement established in the previous section. Figure 7 shows the coverage map for an IEEE 802.11 network[2] in the downstream direction, i.e., from the access point to the points within the cell. The upstream data rate to the access point from all the points within the cell is shown in Fig. 8. The results shown in these coverage maps demonstrate that the maximum rate of 11 Mbps is sustainable only up to about 65% of the radius (R) of the cell in upstream direction while only up to about 60% of the radius in the downstream. Beyond that distance the data rate starts decreasing.

Under the same conditions, we again calculated the coverage map, now assuming that the interfering nodes that are more than $R/2$ units from their access point transmit at a power reduced by a factor of 3. We present the results for the values R/2 and power reduction factor 3 solely for illustrative purposes. A more rigorous simulation study to select a suitable hop distance and power reduction factor in a network with randomly located devices is being planned. Also note that we do not consider forwarding in the downstream direction, the expected improvement is solely because of the reduced transmission power of the interfering nodes. The downstream coverage map that is obtained in this case is shown in Figure 9. Now the maximum rate of 11 Mbps is sustained up to 80% of the radius of the cell. This advantage can be achieved if such a reduction in power by the edge nodes is supported by intermediate nodes forwarding their upstream data traffic to the access point. The negative impact of such a reduction in the power of transmission will be felt as reduced SIR experienced by the forwarding nodes when they receive the frames from the edge nodes. In order to study this impact, we estimated the coverage map again, under the following

[2]The regions outside the hexagonal structure in the figures should be ignored.

assumptions:

- For source nodes less than $R/2$ units from the center, the upstream transmission is direct to the access point at the normal transmission power.
- For source nodes above $R/2$ units from the center, a forwarding node is selected between 40% and 50% of the radius R from the access point in the same direction as the source in consideration. The SIR is calculated at the forwarding node for the transmission from that source with the transmission power of the source reduced by a factor of 3. Once again, this simplifying assumption is made for illustrative purposes to study the effect of power reduction on the SIR at the forwarding nodes.
- The interfering nodes will transmit at full power if they are less than $R/2$ units from their respective access points and reduce their power of transmission by a factor of 3 otherwise.

Figure 10 shows the data rate experienced by each point in the cell under these conditions. This result shows that in a majority of the cell area, upstream transmissions are sustainable at the high data rates of 11 Mbps or 5.5 Mbps. However, closer to the edge of the cell the nodes will experience low upstream transmission rates because of the reduced transmission power. Even though such reduced data rates are seen at the edges, the overall improvement in coverage in terms of improved data rate justifies continued investigation of multi-hop extensions to the 802.11 MAC.

VII. Conclusions and Future Work

Most research on extending the 802.11 MAC using multi-hop communication has primarily focused on increasing the coverage area of a single access point. In this paper, we present and discuss the viability of two more advantages of using multi-hop transmissions; improved bandwidth availability in a multi-rate environment and improved coverage at the edges of 802.11 networks.

In terms of future work, modifications to the basic MAC protocol to enable multi-hop transmissions with backward compatibility to the current MAC specification should be designed. Adapting the MAC protocol to allow forwarding nodes opportunistic access will provide better incentive for nodes to participate in such forwarding. Additionally work needs to be done in determining the optimal forwarding nodes while maintaining all the nodes at higher rates[12]. Further analysis of the trade-off between reducing transmission power, maintaining the transmission rate and maintaining the carrier-sense algorithm within a cell is needed. Also, a more comprehensive study should be done to optimize the power of transmission and the hop-distance to reach the forwarding node in order to fully realize the benefits of reducing transmission power at the edge nodes.

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