Wireless Personal Communications (2007) 43:65–87
DOI 10.1007/s11277-006-9239-y

To Forward or not to Forward – that is the Question

SATHYA NARAYANAN[1] and SHIVENDRA S. PANWAR[2]

[1]*Panasonic Princeton Laboratory, Two Research Way, 3rd Floor, Princeton, NJ 08540, USA*
E-mail: sathya@Research.Panasonic.COM
[2]*Department of Electrical and Computer Engineering, Polytechnic University, Brooklyn, NY, USA*
E-mail: panwar@catt.poly.edu

Abstract. We introduced the use of two-hop forwarding to increase the throughput of an 802.11 network in our earlier work (Narayanan et al., *Proceedings of IEEE WCNC'05,* March 2005). Other researchers have also considered the benefits of forwarding in the 802.11 infrastructure mode to increase the total network throughput. But the high-data rate node that forwards data for other nodes will have to spend its energy transmitting this data. Previous work on forwarding implicitly assumed that in an enterprise network, the collective good is sufficient to justify this increased energy expense. However, it is important to address the advantages and the cost of participating in such schemes from the individual forwarding node's perspective. Since a node cannot know whether there are other high-data rate nodes in the network capable and willing to forward data, it needs to assume that it is the only node with the capability to do so. In this paper, we focus our analysis on the cost benefit for such a forwarding node. We quantify the throughput improvement, medium access delay reduction and energy consumption for the forwarding node in a saturated network. The analysis and simulation results demonstrate that in a saturated network, participation in forwarding provides the high-data rate node with significant benefits in throughput and media-access-delay, while increasing the number of bits-per-joule even if it is the only node participating in data forwarding as suggested in this paper. The increase in the bits-per-joule is due to the reduction in the total amount of time needed by the high data rate node to transmit a given number of its *own* application bits. This results in savings in energy expenditure for the forwarding node. Based on these benefits, we conclude that it is unequivocally in the interest of a high data rate node to participate in two-hop forwarding schemes in 802.11 networks.

Keywords: IEEE 802.11, MAC, Wireless LANs, Link adaptation, multi-hop forwarding, Cooperative communications

1. Introduction

The IEEE 802.11 family of protocols define PHY layers operating at different data rates based on the signal strength at the receiver. At present a considerable amount of research effort by us [1–5] and by other research groups [6], has been expended in analyzing the use of two-hop forwarding to mitigate the negative impact of low-data rate nodes in the network. These efforts demonstrate the throughput and delay improvements for the entire network when two-hop forwarding schemes are used. In earlier work, we have also investigated the better signal-to-interference ratio experienced by nodes in a multi-cell environment when two-hop forwarding is used. These improvements, which clearly benefit low-data rate nodes, by themselves do not provide enough motivation for a high-data rate node to participate in such schemes because the improvements are realized only when all the high-data rate nodes participate in forwarding. Along with the design of a backward compatible protocol, providing motivation for the individual nodes to participate in forwarding will play a crucial role in making the incremental deployment of such forwarding schemes possible. Since many of the nodes in the network may be legacy nodes that do not support forwarding, each high-data rate node will have to assume that it is the only node capable of forwarding data. We looked at whether the high-data rate node can expect any benefits for itself even under this assumption and conclude, through analysis and simulation, that there are throughput and delay improvements for the high-data rate node. We also look at the cost in terms of energy consumption for such a forwarding node by calculating the transmitted bits-per-joule, with and without forwarding. Surprisingly, we can demonstrate that over a long period of time the forwarding node can achieve a higher number of bits-per-joule, and hence can save on its energy expenditure by participating in forwarding schemes. This seemingly counter-intuitive result is due to the fact that by forwarding another node's data, the high-data rate node is able to complete the transmission of its own data in a significantly shorter-time interval. This reduced time results in idle energy savings for the high-data rate node that exceed the energy expended by it in forwarding third-party data.

Since we demonstrate these advantages assuming that the node in question is the only node participating in forwarding, 802.11 nodes with forwarding capability do not have to wait for wide adoption before starting to forward data for low-data rate node. Thus incremental deployment of 802.11 nodes with forwarding capability is possible.

1.1. Related Work

References [1–6] present the advantages from the total network throughput perspective when forwarding is used in 802.11 MAC. These results show that the effective throughput of a WLAN can be almost doubled in some cases with the use of forwarding. Additionally, [1] showed that a reduction in interference in a dense deployment is a potential benefit of forwarding.

Reference [7] argues, accurately, that a selfish node has two disincentives for forwarding other nodes traffic: the energy expenditure (real cost) and possible delay for its own traffic (opportunity cost). Reference [7] continues to show a mechanism based on *co-operation through bribery* where forwarding nodes are reimbursed through a pricing model. Instead of requiring any such pricing model, in this paper we demonstrate that in 802.11 infrastructure mode networks, high-data rate nodes have inherent incentives both in terms of throughput and energy consumption to participate in forwarding. In other words, cooperation is a *win–win* proposition and a pricing model scheme is therefore not needed.

2. Review of the IEEE 802.11b MAC

IEEE 802.11 [8] specifies a CSMA/CA MAC for use on wireless networks, while 802.11b [9], and 802.11g [10] are defined for the 2.4 GHz band and 802.11a in the 5 GHz band. Both 802.11b and 802.11g define 11 channels for operation, but only three are non-overlapping. The MAC specification allows IEEE 802.11b wireless nodes to operate at 1, 2, 5.5, and 11 Mbps based on the quality of the signal it receives from the access point. The algorithm to choose a suitable bit-rate itself is not defined by the specification. The mechanism of access defined by the 802.11 specification is called Distributed Coordination Function (DCF). DCF is a CSMA/CA scheme that uses an exponential backoff when a collision occurs. The MAC algorithm requires each node to randomly backoff even before the first transmission to avoid collision, while using an acknowledgment (ACK) to detect collision. The recipient of a data frame is allowed to transmit an ACK message after a short interval called SIFS (10 μs), while for data transmission the nodes are required to sense an idle channel for a longer interval called DIFS (50 μs). The difference in these time durations reduces the chances of an ACK collision.

IEEE 802.11 MAC also defines a virtual carrier sense mechanism based on a Request To Send (RTS) and a Clear To Send (CTS) message exchange.

A brief summary of DCF can be found in [11]. Readers are referred to the IEEE specification [8] for details.

3. Two-Hop Forwarding

Due to the inherent long-term access fairness [12] of the 802.11 MAC design, in a saturated network every node in the network will receive an equal expected number of access opportunities to transmit its data. As the number of low-data rate nodes in the network increases, total throughput drops because the low-data rate nodes occupy the channel for longer durations to transmit the same amount of data. In our earlier work [1, 3], we suggested the use of two-hop forwarding to mitigate this reduction of throughput.

The basic idea is for the high-data rate nodes in the network to assist low-data rate nodes in their transmission by forwarding their traffic. Such forwarding is to be done only when the total transmission time from the source node to the forwarding node and the forwarding node to the final destination is less than the time taken for a direct transmission from the source node to the destination. To avoid the loss of one transmission opportunity for the forwarding node, we recommend that the forwarding be done immediately after a SIFS interval, rather than after contention.

It has been demonstrated by us and others [6] that such two-hop forwarding leads to higher total network throughput. Since the increased throughput is shared equally by all the nodes in the network, it is not clear if there is enough incentive for a high-data rate node to participate in forwarding. Also, the network is likely to have some nodes capable and willing to forward while other nodes may not. In such a scenario, the possible energy spent by the forwarding node in transmitting data for other nodes may not be justified by the increased throughput experienced by itself. Therefore, we consider the scenario shown in Figure 1, where a high-data rate node (either with a 11 Mbps or 5.5 Mbps data rate to the access point) FW has to decide whether to forward data traffic for low-data rate nodes.

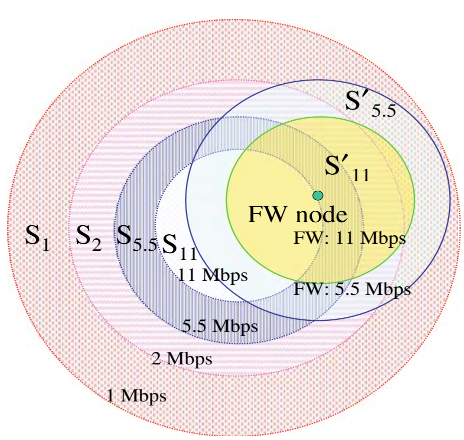

Figure 1. Forwarding node.

We analyze the throughput, delay, and energy consumption of such a node in Sections 4, 4.1, and 5, respectively. This analysis is done assuming the worst case scenario where none of the other high-data rate nodes participate in forwarding. We consider the worst case scenario because a high-data rate node cannot know the forwarding status of other nodes and it needs to make its choice assuming the worst case scenario that no other node is forwarding data traffic (see Section 7). Additionally, this assumption allows us to address the question of whether incremental deployment of forwarding schemes is possible or whether multiple nodes participating in forwarding are needed to realize the advantages of forwarding.

4. Analysis of Forwarding Node Throughput

We developed an expression for the total saturation throughput for each node (S_{node}) in [1] as follows:

Total saturation throughput S_{node} in bits per second for each node in the network,

$$S_{\text{node}} = \frac{1}{N}\frac{(1-p)\cdot l}{\sum_X f_X T_X}, \tag{1}$$

where N is the number of nodes in the network, p the probability of collision as calculated in [1], f_X the fraction of nodes at data rate X, and T_X is the transmission time for a packet with l bits.

The average bit transmission time is given by

$$T_{\text{Avg}} = \sum_X \frac{f_X}{X}$$

and the denominator $\sum_X f_X T_X$ in equation (1) is equal to $(\text{MACHEADER}+l)T_{\text{Avg}}+T_{\text{Overhead}}$. T_{Overhead} is the sum of DIFS, SIFS, and the PLCP overhead and MACHEADER is the size of the 802.11 MAC header.

Assume the ranges for 11, 5.5, 2, and 1 Mbps transmission to be r_{11}, $r_{5.5}$, r_2, and r_1, respectively. In order to analyze the throughput improvement for the forwarding node, we first define a function A as below,

$$A(r_a, r_b, r_c, d) = S_{r_a,r_b}(d) - S_{r_c,r_b}(d),$$

where $S_{r_a,r_b}(d)$ is the area of overlap for two circles of radius r_a and r_b with their centers at a distance d from each other. A is used to find the fraction of low data rate nodes that can be assisted by a high-data rate node at a distance d from the access point. For example, the area calculated as $A(r_1, r_{11}, r_2, d)$ is the intersection of the areas S'_{11} and S_1 in Figure 1.

The following analysis can be better understood by looking at the areas marked in Figure 1. For the forwarding node shown in Figure 1, the intersection of the areas S'_{11} and S_1 depicts the area from which nodes at the 1 Mbps range can reach the forwarding node at a 11 Mbps first hop. Similarly, the intersection of the areas $S'_{5.5}$ and S_1 depicts the area from which nodes at the 1 Mbps range can reach the forwarding node with a 5.5 Mbps first hop. In order to calculate the fraction of nodes at the 1 Mbps range that can reach the forwarding node at the corresponding rate, we need to calculate the marked areas as a fraction of the coverage area. For a given high-data rate node at x Mbps (x could be 11 Mbps or 5.5 Mbps), we use $q^{\text{one}}_{f,x}$ to denote the fraction of nodes at the 1 Mbps range that can reach the access point through the high-data rate node with a f Mbps first hop and a x Mbps second hop. $q^{\text{two}}_{f,x}$ is defined similarly for nodes at the 2 Mbps range.

The fraction of nodes at the 1 Mbps range that can reach a given forwarding node (with data rate x Mbps), through a 11 Mbps first hop is given by the ratio of the intersection of S'_{11} and S_1 in Figure 1 over the total coverage area. This ratio is $A(r_1, r_{11}, r_2, d)/\pi r_1^2$. Since the forwarding node could be at a distance anywhere between r_l and r_h from the access point, where $r_l = r_{11}$ and $r_h = r_{5.5}$ for forwarding node data rate ($x =$) 5.5 Mbps, and $r_l = 0$ and $r_h = r_{11}$ for forwarding node data rate ($x =$) 11 Mbps, $q^{\text{one}}_{11,x}$ is given by

$$q^{\text{one}}_{11,x} = \int_{r_l}^{r_h} \frac{2r}{r_h^2 - r_l^2} \frac{A(r_1, r_{11}, r_2, r)}{\pi r_1^2} dr,$$

and the fraction nodes at the 1 Mbps range that can reach the forwarding node through a 5.5 Mbps hop is given by

$$q^{\text{one}}_{5.5,x} = \int_{r_l}^{r_h} \frac{2r}{r_h^2 - r_l^2} \frac{A(r_1, r_{5.5}, r_2, r) - A(r_1, r_{11}, r_2, r)}{\pi r_1^2} dr.$$

The area calculated by the expression $A(r_1, r_{5.5}, r_2, r) - A(r_1, r_{11}, r_2, r)$ is the intersection of areas $S'_{5.5}$ and S_1 in Figure 1.

Similarly, the fraction of nodes at the 2 Mbps range from the AP that can reach the forwarding node through a 11 Mbps first hop is given by

$$q^{\text{two}}_{11,x} = \int_{r_l}^{r_h} \frac{2r}{r_h^2 - r_l^2} \frac{A(r_2, r_{11}, r_{5.5}, r)}{\pi r_1^2} dr,$$

while for a 5.5 Mbps first hop, the fraction is

$$q^{\text{two}}_{5.5,x} = \int_{r_l}^{r_h} \frac{2r}{r_h^2 - r_l^2} \frac{A(r_2, r_{5.5}, r_{5.5}, r) - A(r_2, r_{11}, r_{5.5}, r)}{\pi r_1^2} dr.$$

In the case of a low-data rate node at the 1 Mbps range, the first hop rate could also be 2 Mbps. This fraction of nodes with first hop of 2 Mbps is given by

$$q^{\text{one}}_{2,x} = \int_{r_l}^{r_h} \frac{2r}{r_h^2 - r_l^2} \frac{A(r_1, r_2, r_2, r) - A(r_1, r_{5.5}, r_2, r)}{\pi r_1^2} dr.$$

For a given node at the high-data rates of 11 Mbps, if it chooses to provide assistance to low-data rate nodes in their transmission, the average bit transmission time will become

$$\begin{aligned} T^{11}_{\text{Avg}} = {} & ((f_{11} + q^{\text{one}}_{y,11} + q^{\text{two}}_{z,11} + q^{\text{one}}_{11,11} + q^{\text{two}}_{11,11})/(11 \cdot 10^6) \\ & + (f_{5.5} + q^{\text{one}}_{5.5,11} + q^{\text{two}}_{5.5,11})/(5.5 \cdot 10^6) \\ & + (f_2 - q^{\text{two}}_{z,11} + q^{\text{one}}_{2,11})/(2 \cdot 10^6) + (f_1 - q^{\text{one}}_{y,11})/(1 \cdot 10^6)), \text{ and} \end{aligned}$$

$$T^{11}_{\text{Forw}} = T^{11}_{\text{Avg}} * (l + \text{MACHEADER}) + (q^{\text{one}}_{y,11} + q^{\text{two}}_{z,11}) \cdot T^{\text{Hop}}_{\text{overhead}} + T_{\text{Overhead}},$$

where $q_{y,11} = q_{11,11} + q_{5.5,11} + q_{2,11}$, and $q_{z,11} = q_{11,11} + q_{5.5,11}$.

Similarly for a 5.5 Mbps forwarding node,

$$T^{5.5}_{\text{Avg}} = ((f_{11} + q^{\text{one}}_{11,5.5} + q^{\text{two}}_{11,5.5})/(11 \cdot 10^6) + (f_{5.5} + q^{\text{one}}_{y,5.5} + q^{\text{two}}_{z,5.5} + q^{\text{one}}_{5.5,5.5} + q^{\text{two}}_{5.5,5.5})/(5.5 \cdot 10^6) + (f_2 - q^{\text{two}}_{z,5.5} + q^{\text{one}}_{2,5.5})/(2 \cdot 10^6) + (f_1 - q^{\text{one}}_{y,5.5})/(1 \cdot 10^6)),$$

$$T^{5.5}_{\text{Forw}} = T^{5.5}_{\text{Avg}} \cdot (l + \text{MACHEADER}) + (q^{\text{one}}_{y,5.5} + q^{\text{two}}_{z,5.5}) \cdot T^{\text{Hop}}_{\text{overhead}} + T_{\text{Overhead}}.$$

Hence such a forwarding node will experience the following increased saturation throughput,

$$S_X = \frac{1}{N} \frac{(1-p) \cdot l}{T^X_{\text{Forw}}},$$

where $X = 5.5$, 11. p is the probability of collision in a 802.11 network as calculated in [1].

The calculated results of the throughput improvements are presented in Figures 2 and 3. It is straightforward to extend this analysis to an 802.11g network. It should be noted that a 5.5 Mbps node achieves a higher throughput improvement by participating in two-hop forwarding compared to the improvement achieved by a 11 Mbps node. This result is due to that fact that a 5.5 Mbps node has a higher probability of being closer to low-data rate nodes and will be able to assist more of them as compared to a 11 Mbps node which is closer to the access point. As more high-data rate nodes start participating in forwarding the overall throughput improvement will become higher reaching the maximum demonstrated in [1, 3].

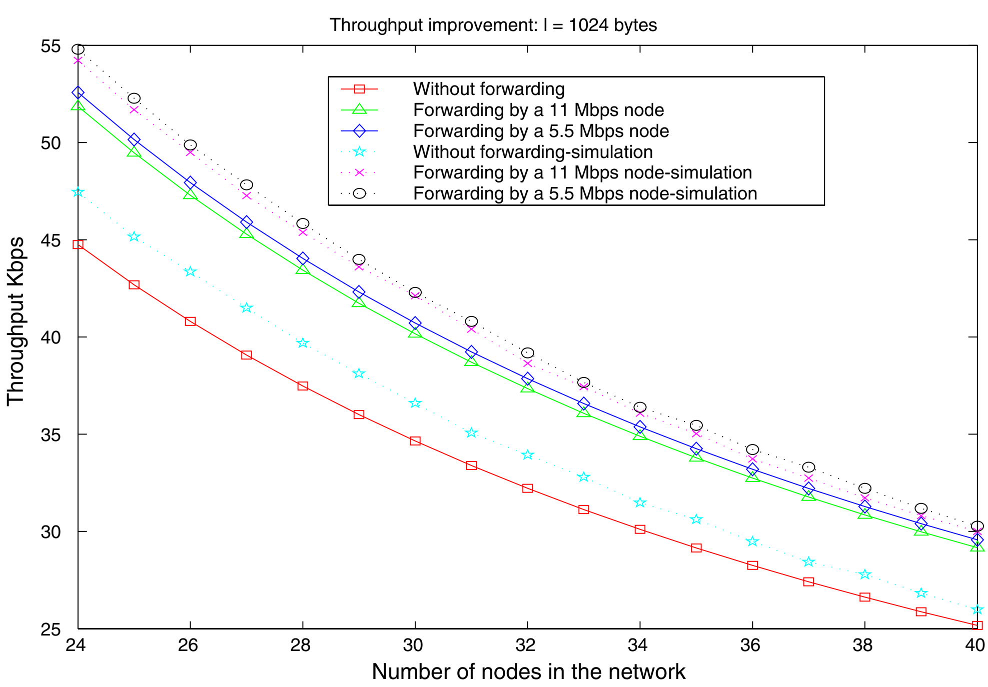

Figure 2. Throughput improvement.

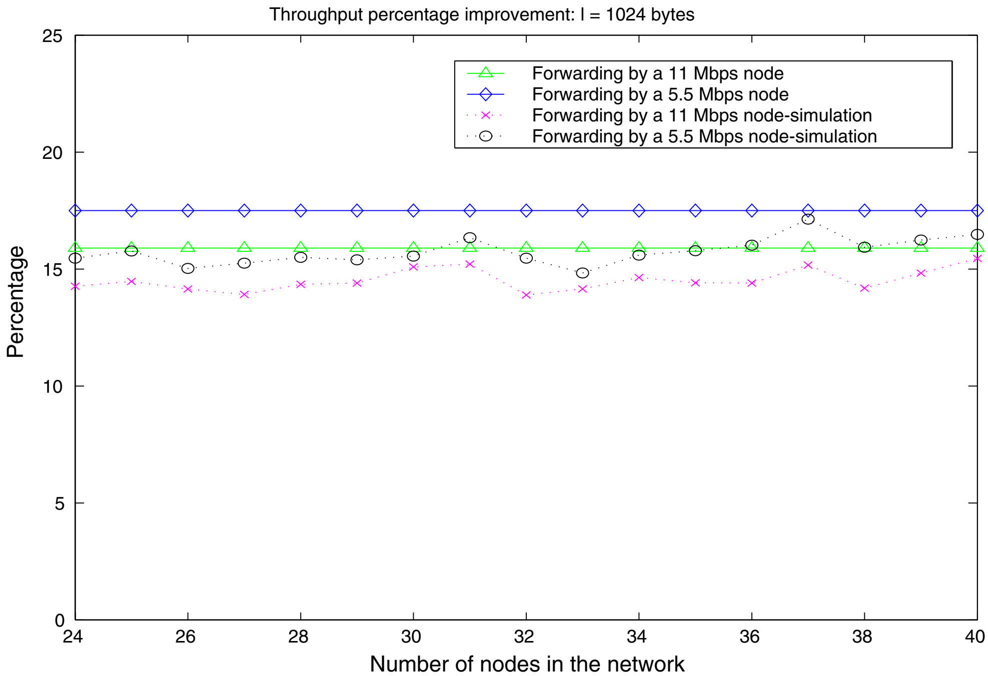

Figure 3. Throughput percentage improvement.

4.1. Analysis of Forwarding Node Media Access Delay

An analytical model for the media access delay experienced by each 802.11 node is presented in [13]. By substituting, $T_s = \sum_X f_X T_X$ in the expressions derived in [13], the media access delay can be calculated when forwarding is not used. Similarly, substituting $T_s = T^{11}_{\text{Forw}}$ and $T_s = T^{5.5}_{\text{Forw}}$, the media access delay experienced when a 11 and 5.5 Mbps are forwarding data, respectively, can be calculated. The results are presented in Figures 4 and 5.

4.2. Improvement with respect to packet length

From the results shown in Figures 3 and 5, it is seen that the percentage improvement achieved by forwarding is independent of the number of nodes in the network. This result follows from the fact that the number of nodes (N) appears both in the numerator and denominator of the percentage calculation and hence cancel out. Therefore instead of varying the number of nodes, we calculated the throughput improvement and delay improvement for different packet lengths. The results are shown in Figures 6–9. As expected, the improvement gained by two-hop forwarding increases as the packet length increases because of the fixed overhead involved in transmitting a packet on the channel. It should also be noted that the percentage improvement plateaus at about 19% for throughput and 16% for media access delay.

5. Analysis of Energy Consumption

In order to look at the energy cost to a forwarding node associated with forwarding another nodes' data, we need to keep the following points in mind:

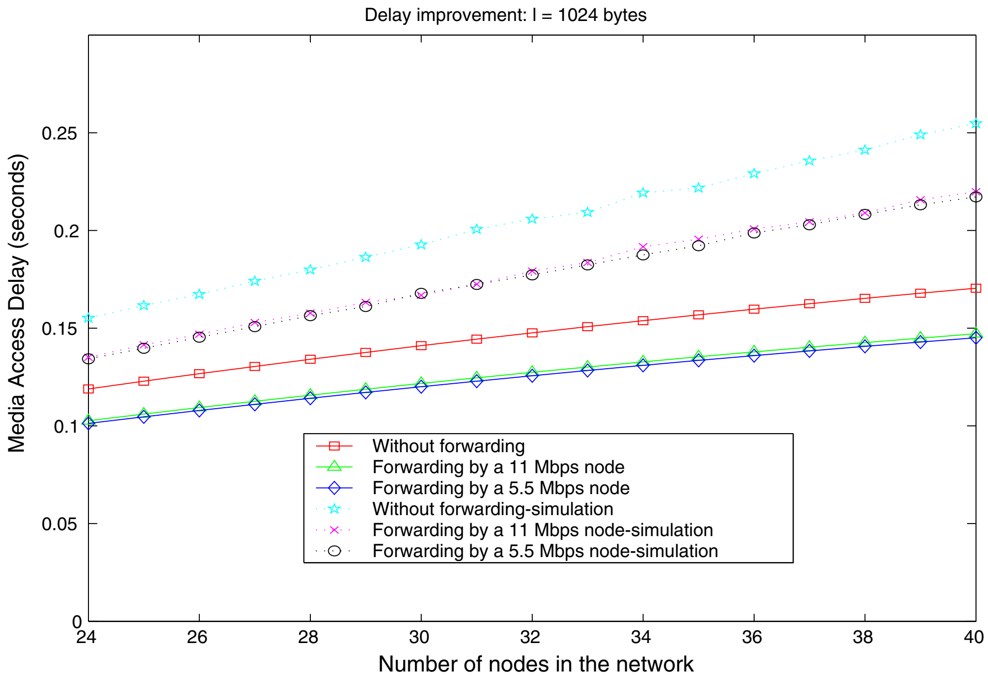

Figure 4. Delay improvement.

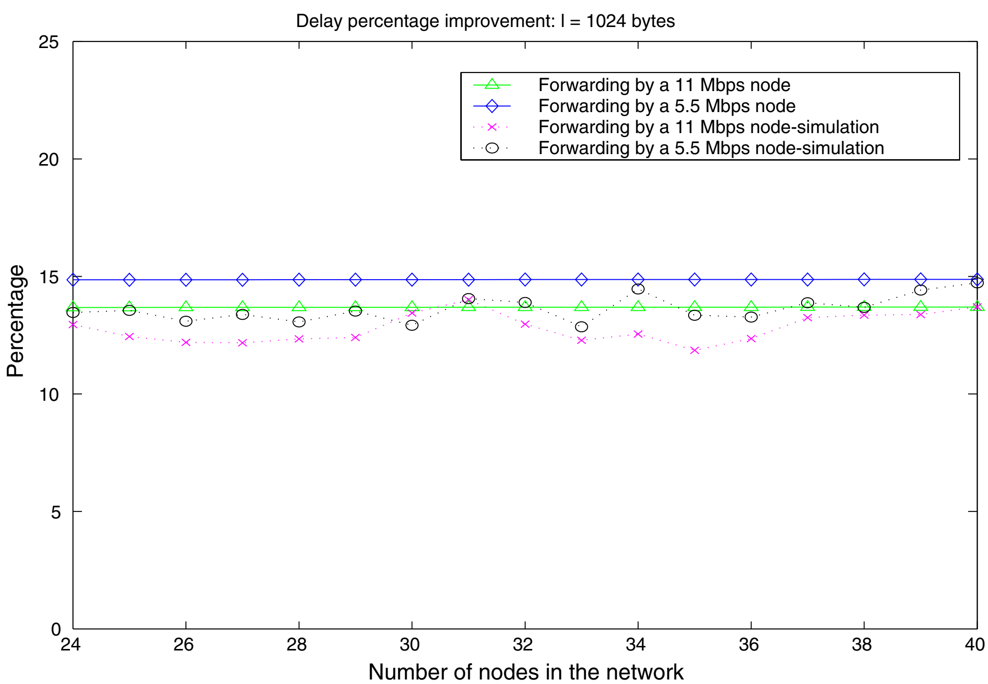

Figure 5. Delay percentage improvement.

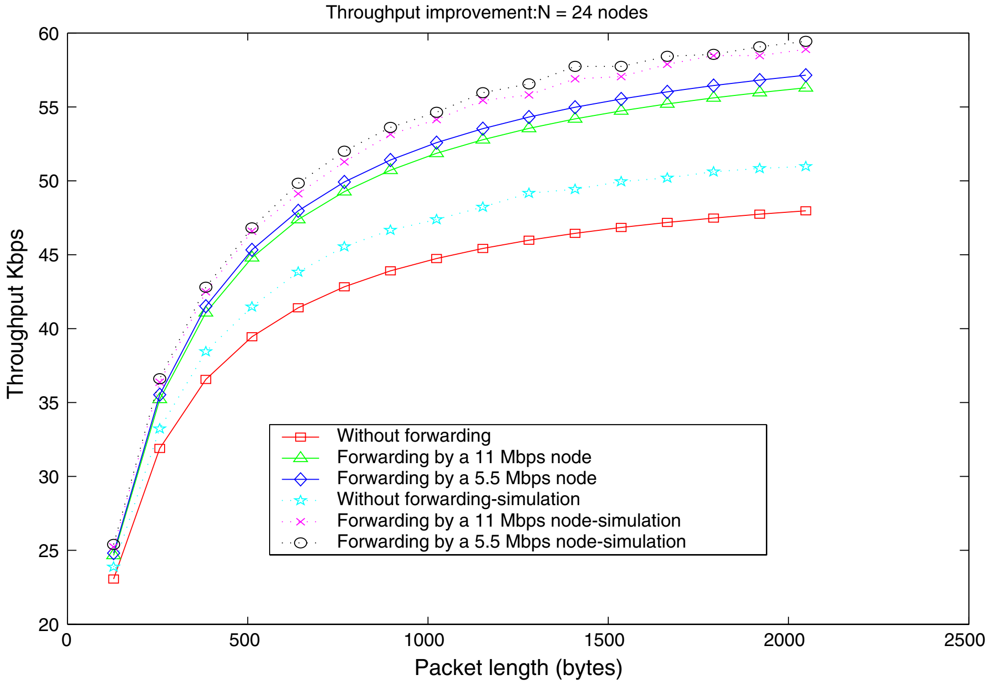

Figure 6. Throughput vs packet length.

- Similar to our discussion on throughput, we consider a saturated network with every node having a packet to transmit all the time.
- We analyze the energy expense for a given number of application bits (L) for the high-data rate node. The underlying assumption is that the node shuts down after it is done transmitting its application bits or constantly has bits to send. Obviously, if a node stays on-line transmitting data for other nodes with little or no traffic of its own to send, the bits-per-joule ratio for this node will be lower leading to a higher energy cost.

Given that a node (referred to as Node_A) has to achieve the data transfer of L bits and there are N nodes in the network, the energy used by Node_A will be:

$$E = T_{\text{T}} P_{\text{T}} + T_{\text{R}} P_{\text{R}} + T_{\text{L}} * ((1 - F_{\text{R}}) P_{\text{I}} + F_{\text{R}} P_{\text{R}}), \qquad (2)$$

where P_{T}, P_{R}, and P_{I} are the power consumption during the transmission, reception, and idle states of the WLAN card. T_{T} and T_{R} are the time Node_A will spend transmitting frames and receiving frames, respectively, while T_L is the time Node_A will spend listening to packet transmissions going on between two other nodes. When such a transmission between two other nodes occurs, a fraction (F_{R}) of the packet will be received at Node_A before it realizes the transmission is not meant for itself and switches to idle mode. This behavior is captured by the last component of equation (2). Reference [14] uses a similar model for estimating the energy consumption, but does not differentiate between the states where the node is receiving a packet and where the node is idle.

We take into consideration an idle state as follows: after the node recognizes that the frame being transmitted is not meant for itself, it switches to an idle state where its energy consumption is less than in a receiving state. As a first step approximation, let us ignore the higher

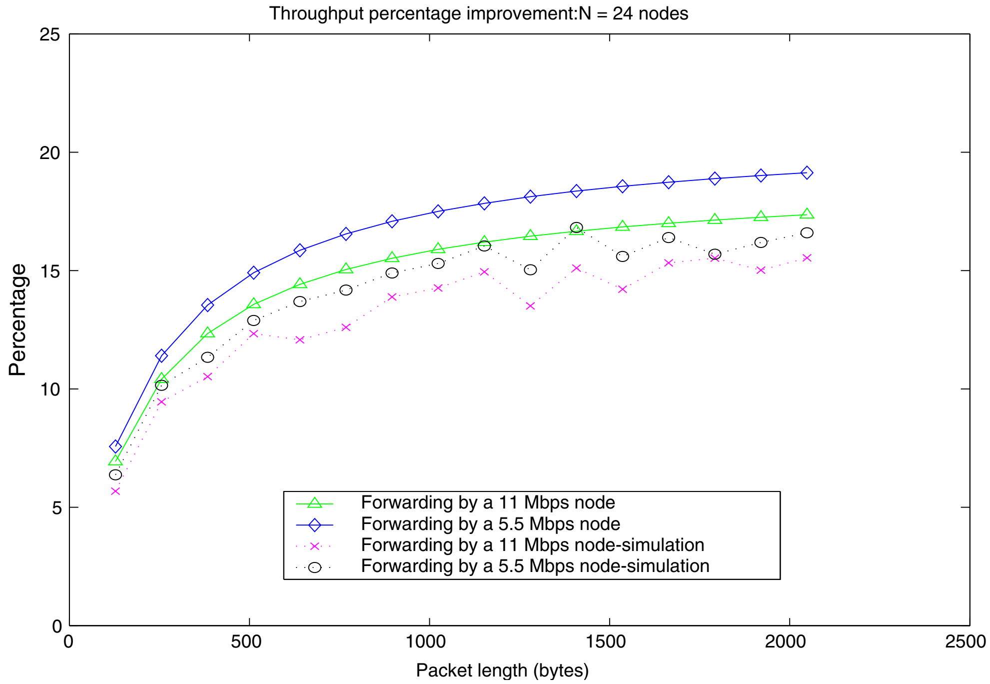

Figure 7. Throughput percentage vs packet length.

layer control packets (like FTP/TCP control packets) and assume that the data transfer is from the 802.11 node to a server on the network. Under such a scenario, we consider only data transmission from the 802.11 node and assume no frames are received by it.

T_L is the time during which a packet transmission not addressed to Node_A is taking place. The power consumption P_L for these packets will be

$$P_L = (1 - F_\text{R})P_I + F_\text{R} P_\text{R}$$

as shown in equation (2), where

$$F_\text{R} = \frac{\text{PLCP} + (10 * 8) * T_\text{Avg}}{\text{PLCP+ (MACHEADER} + l) * T_\text{Avg}}$$

and

$$F_\text{R}(X) = \frac{\text{PLCP} + (10 * 8) * T(X)}{\text{PLCP+ (MACHEADER} + l) * T(X)},$$

where $T(11)$ is T_Avg^{11} and $T(5.5)$ is $T_\text{Avg}^{5.5}$. The fraction F_R is the fraction of a frame transmission that a node must receive and process before it can know that the frame is not addressed to itself. This fraction will be the PLCP header and the first 10 bytes of the MAC header, since the destination header of the packet is the third byte to tenth byte of the MAC header. Once the destination address is processed, Node_A can switch its WLAN card to idle mode.

For the non-forwarding case, the transmission time for the high-data rate (X Mbps) node for a given number of bits L will be

$$T_\text{T}(X) = L/l * (\text{PLCP} + (\text{MACHEADER} + l)/X),$$

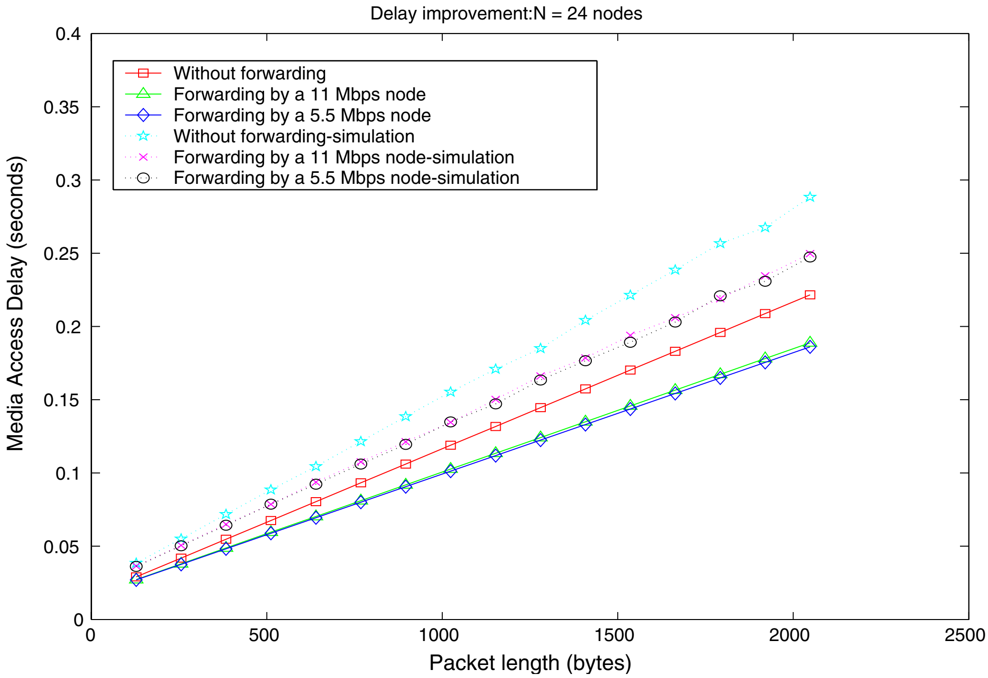

Figure 8. Delay vs packet length.

where X is the data rate of the forwarding node. The fraction L/l provides the number of transmissions the node will have to make to transmit a total of L bits. Similarly, the listening time and receiving time are

$$T_L = L/l * (N - 1) * (\text{PLCP+(MACHEADER+}l) * T_{\text{Avg}}),$$

where the $(N - 1)$ factor captures the transmission by all the other nodes to the access point, and

$$T_{\text{R}} = L/l * N * \text{Backoff},$$

where Backoff is the time spent in the random backoff required by 802.11 MAC. If the node chooses to participate in forwarding, then the transmission time T_T^{Forw} as a function of the data rate is calculated as follows:

$$T_T^{\text{Forw}}(X) = L/l * (\text{PLCP} + (\text{MACHEADER} + l)]/X + N * (q_{y,X}^{\text{one}} + q_{z,X}^{\text{two}}) * (\text{PLCP+(MACHEADER} + l)/X)),$$

where the $N * (q_{y,X}^{\text{one}} + q_{z,X}^{\text{two}})$ component captures the fraction of the nodes at low data rates that will be helped by the forwarding node. Similarly, the listen time T_L^{Forw}, and receive time T_R^{Forw} as a function of the data rate are

$$T_R^{\text{Forw}}(X) = L/l * (N * \text{PLCP} * (q_{y,X}^{\text{one}} + q_{z,X}^{\text{two}}) + N/10^6 * (q_{2,X}^{\text{one}}/2 + (q_{5.5,X}^{\text{one}} + q_{5.5,X}^{\text{two}})/5.5 + (q_{11,X}^{\text{one}} + q_{11,X}^{\text{two}})/11) * (\text{MACHEADER} + l) + N * \text{Backoff}),$$

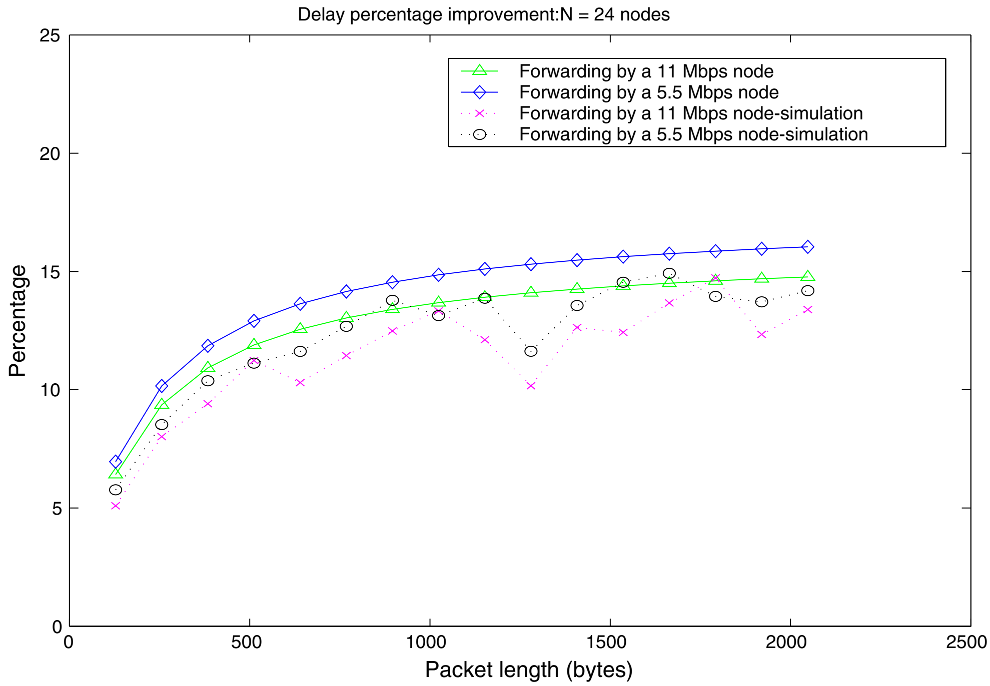

Figure 9. Delay percentage vs packet length.

$$T_L^{\text{Forw}}(X) = L/l * (N-1) * (\text{PLCP} + (\text{MACHEADER} + l) * T_{\text{Avg}}^X) \\ - (T_R^{\text{Forw}} - L/l * N * \text{Backoff}).$$

Substituting $T_T^{\text{Forw}}(X)$, $T_R^{\text{Forw}}(X)$, and $T_L^{\text{Forw}}(X)$ for T_{T}, T_{R}, and T_{L}, respectively, in equation (2) will give us the energy consumption for the high-data rate node if it participates in forwarding. The results from calculations for the non-forwarding case and the forwarding case, with transmission power at 2.05 W, receive power at 0.95 W, and idle power at 0.85 W [15] are shown in Figures 10 and 11.

The energy gain calculated as the difference between the energy consumption without forwarding and with forwarding is shown in Figures 12 and 13 (considering the power consumptions for transmit, receive, and idle states as 1.34, 0.90, 0.73 W, respectively, from [16] further increases the energy gain due to forwarding). A positive difference shows that the energy consumed by the device for transmitting a particular amount of bits is higher without forwarding. This difference is due to the fact that when participating in forwarding, high-data rate nodes have a lower idle time since they spend less time waiting for low-data rate nodes to complete their transmissions. Over time, this saving in idle power more than compensates for the additional energy spent in receiving and transmitting data for other nodes. The negative gain seen in Figure 13 for 256 byte packets is due to the fact that the energy expended for the two-hop overhead is higher than the energy saved due to forwarding such small packets.

From the results shown in Figures 10 and 11, we calculate the bits-per-joule with and without forwarding for the high-data rate node. As shown in Table 1, we see that in a saturated network, a high-data rate node can transmit more of its own bits-per-joule if it participates in two-hop forwarding schemes. We also calculated the bits-per-joule for IEEE 802.11g wireless nodes with higher data rates (24, 12, and 6 Mbps) and present the results in Table 1.

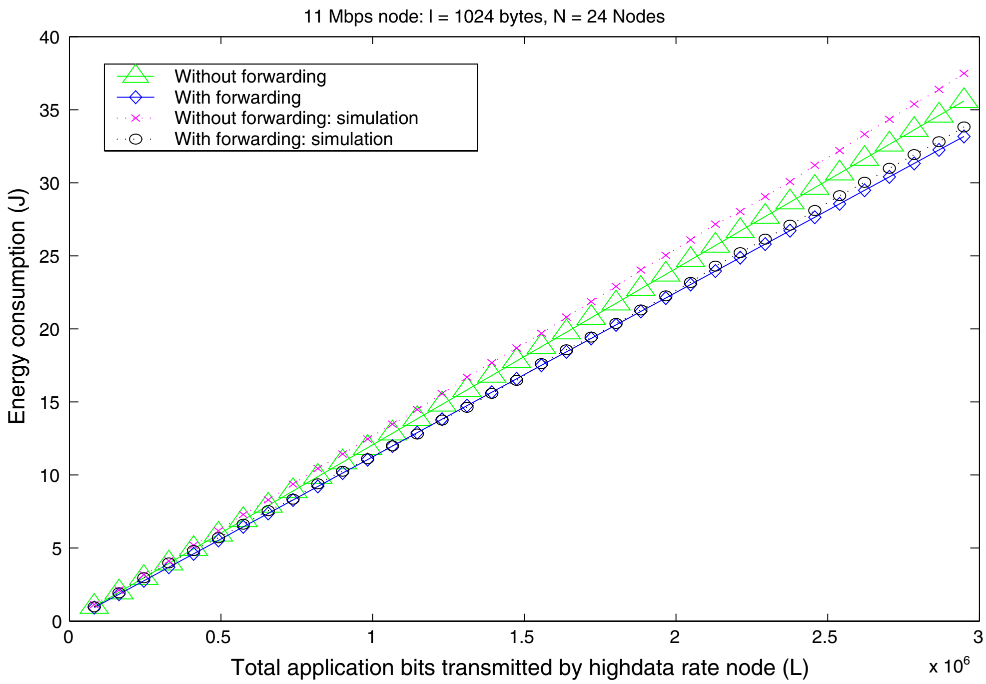

Figure 10. 11 Mbps node – energy consumption.

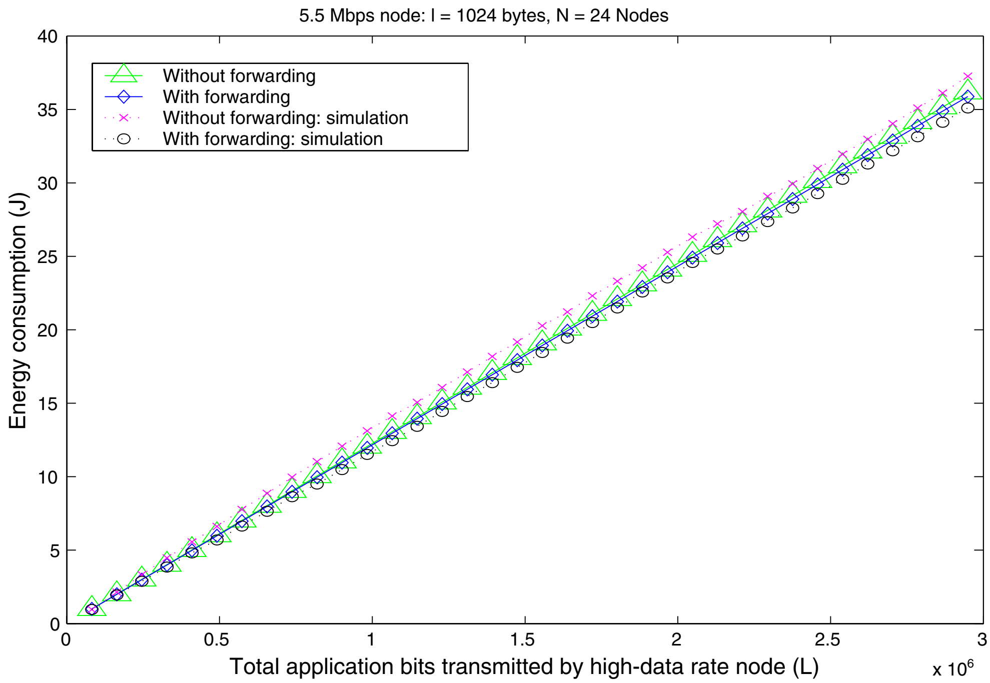

Figure 11. 5.5 Mbps node – energy consumption.

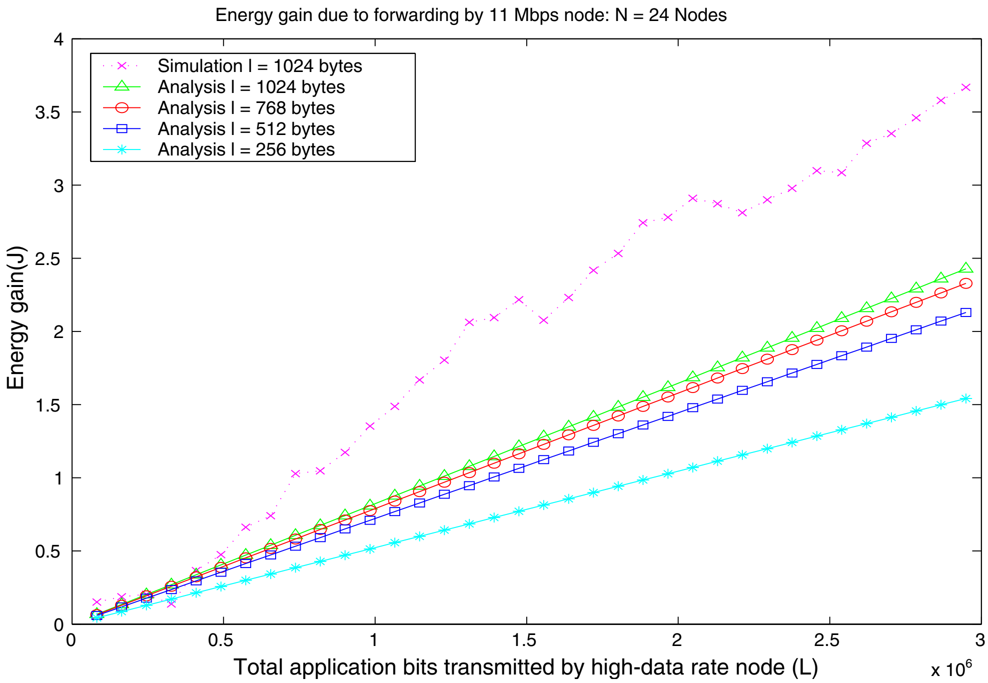

Figure 12. 11 Mbps node – energy gain.

5.1. Discussion on Energy Savings

The energy savings demonstrated for the forwarding node can be better understood by the simplified scenario shown in Figure 14. The figure shows two transmission scenarios, one with a 11 Mbps node not participating in forwarding and the other with the 11 Mbps node forwarding data for the 1 Mbps node. When there is no forwarding, the 11 Mbps node will transmit its own frame and remain idle while the 1 Mbps node transmits its data frame.

However, when two-hop forwarding is used, after transmitting its own frame, the 11 Mbps node will receive a data frame from the 1 Mbps node and transmit that frame to the final destination. By assisting the 1 Mbps node in its transmission, the 11 Mbps node is able to complete transmission of two of its own frames in a shorter duration and switch to the OFF state (see Figure 14). The energy cost associated with forwarding is due to the time spent in receiving and transmitting data from the 1 Mbps node.

The question to be addressed is whether the total energy spent by the 11 Mbps node for a given number of its own application bits (two data frames in the example), is higher when it is not forwarding compared to when it is forwarding data for the 1 Mbps node. The results presented in this paper show that in a saturated network the high-data rate node will save energy by participating in forwarding.

These results are based on the average energy consumption in a saturated network with uniform node distribution. A simple calculation for a single frame of size 1024 bytes, in order to compare the idle energy expense of a high-data rate node when not participating in forwarding, and the receive and transmission energy expense for the same node if it forwards data for another node, is presented in Table 2. Two cases for the transmission, receive and idle power

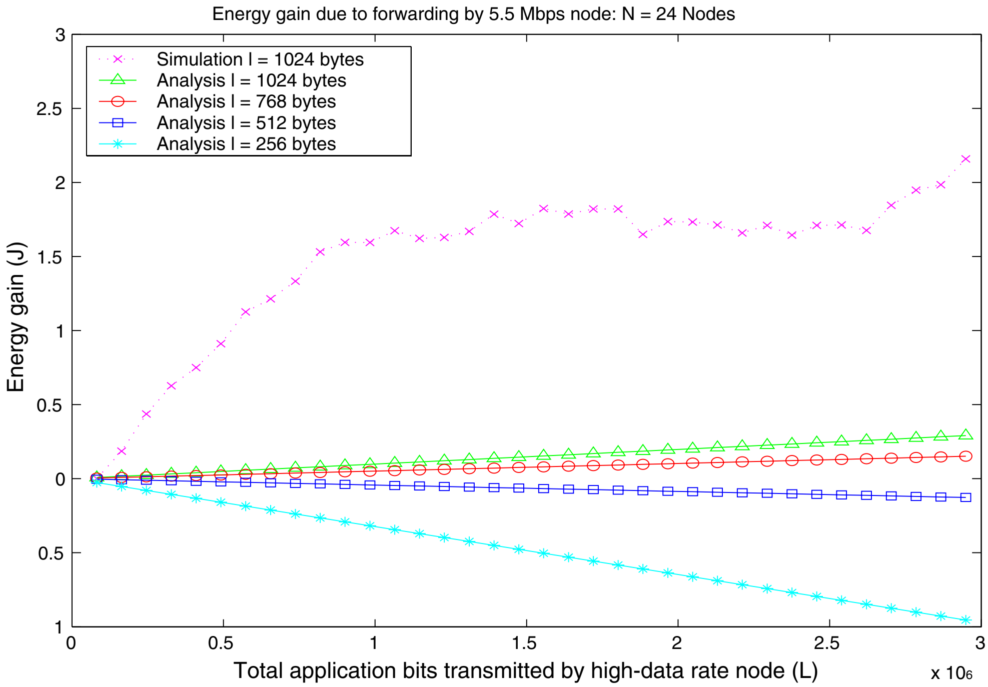

Figure 13. 5.5 Mbps node – energy gain.

consumed by 802.11 cards are shown in the table based on the values from [15, 16]. From the result shown in the first column of Table 2, it can be seen that with the power consumption as specified in [15], a high-data rate node at 5.5 Mbps will lose energy by forwarding data for a 1 Mbps node with a 2 Mbps first hop, while it will save energy if the power consumption is as specified in [16]. Similar conclusions can be made based on the other columns in the Table 2.

To understand the relationship between the idle power (P_I), receive power (P_R), and transmit power (P_T) under which energy savings can be maintained, we define two proportionality variables, α and β, as follows,

$$P_R = \beta P_I$$

Table 1. Bits-per-joule (Pkt Length = 1024 bytes)

	W/o forw(x 10^4)b	With forw(x 10^4)b
11 Mbps node		
Analysis	8.2845	8.8909
Simulation	7.8552	8.7389
5.5 Mbps node		
Analysis	8.1544	8.2206
Simulation	7.7032	8.4592
Data rate		
24 Mbps	9.9596	10.735
12 Mbps	9.8728	10.905
6 Mbps node	9.7037	10.137

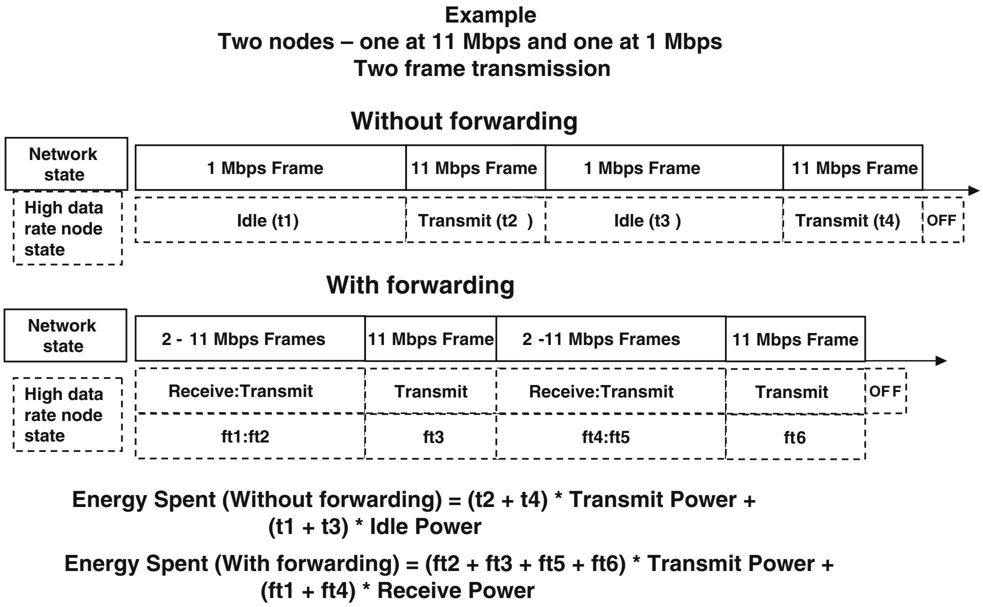

Figure 14. An example.

Table 2. Energy comparison with and without forwarding(l = 1024 bytes)

Slow data rate	1 Mbps	1 Mbps	2 Mbps	2 Mbps	6 Mbps	6 Mbps	6 Mbps
First hop rate	2 Mbps	5.5 Mbps	5.5 Mbps	5.5 Mbps	24 Mbps	24 Mbps	36 Mbps
Second hop rate (High-data rate node)	5.5 Mbps	5.5 Mbps	5.5 Mbps	11 Mbps	24 Mbps	36 Mbps	36 Mbps
Energy saving (J) [15]	−0.000394	0.002165	−0.001432	0.000145	−0.000272	−0.000031	0.000081
Energy saving (J) [16]	0.000018	0.002442	−0.000648	0.000383	−0.000050	0.000107	0.000213

and,

$$P_T = \alpha P_I.$$

Now, the increase in the transmission energy for a high-data rate node (X Mbps) due to participating in forwarding is

$$T_{inc}(X) = (T_T^{Forw}(X) - T_T(X))\alpha P_I.$$

Similarly, the increase in the receiving energy as a function of the data rate X is

$$R_{inc}(X) = ((T_R^{Forw}(X) - T_R) + (T_L^{Forw}(X)F_R(X) - T_L F_R))\beta P_I.$$

The decrease in the idle energy expenditure is

$$I_{dec}(X) = (T_L^{Forw}(X)(1 - F_R(X)) - T_L(1 - F_R))P_I.$$

In order to achieve energy savings from forwarding, the following equation must be true :

$$T_{inc}(X)\alpha + R_{inc}(X)\beta \leq I_{dec}(X). \tag{3}$$

Figures 15 and 16 plot the relationship between α and β based on this equation. In order for the inequality of equation (3) to be maintained any point (α, β) should fall below the lines in the figures. From these figures, we can observe that when P_I and P_R are very close, for example, when β is 1.1, P_T can be as high as $(\alpha =)$ 4.5 times P_I for a 11 Mbps forwarding node to experience energy gain (with 1024 byte packets), while a 5.5 Mbps node requires α to be less than 2.5 to achieve energy savings.

5.2. Analysis of Energy Consumption for the Entire Network

So far in this section, we have looked at the energy consumption for a single forwarding node in a 802.11 network. In this section, we relax the assumption of a single forwarding node to include multiple forwarding nodes, i.e., we consider the scenario where all high-data rate nodes in the network participate in the forwarding scheme and look at the energy consumption for the entire network for a given amount of traffic (denoted by L bits). We derive the expressions for transmission time($\mathrm{TT}_{\mathrm{network}}$), receive time($\mathrm{TR}_{\mathrm{network}}$), and listen time ($\mathrm{TL}_{\mathrm{network}}$) for all the nodes in the network both with and without forwarding. The transmission time for a single MAC frame is

$$T_{\mathrm{MAC}} = (\mathrm{MACHEADER} + l) \cdot T_{\mathrm{Avg}} + \mathrm{PLCP},$$

while the transmission time with forwarding is

$$T^{\mathrm{Hop}}_{\mathrm{MAC}} = (\mathrm{MACHEADER} + l) \cdot T^{\mathrm{Hop}}_{\mathrm{Avg}} + \mathrm{PLCP} + (f'_1 + f'_2) * \mathrm{PLCP},$$

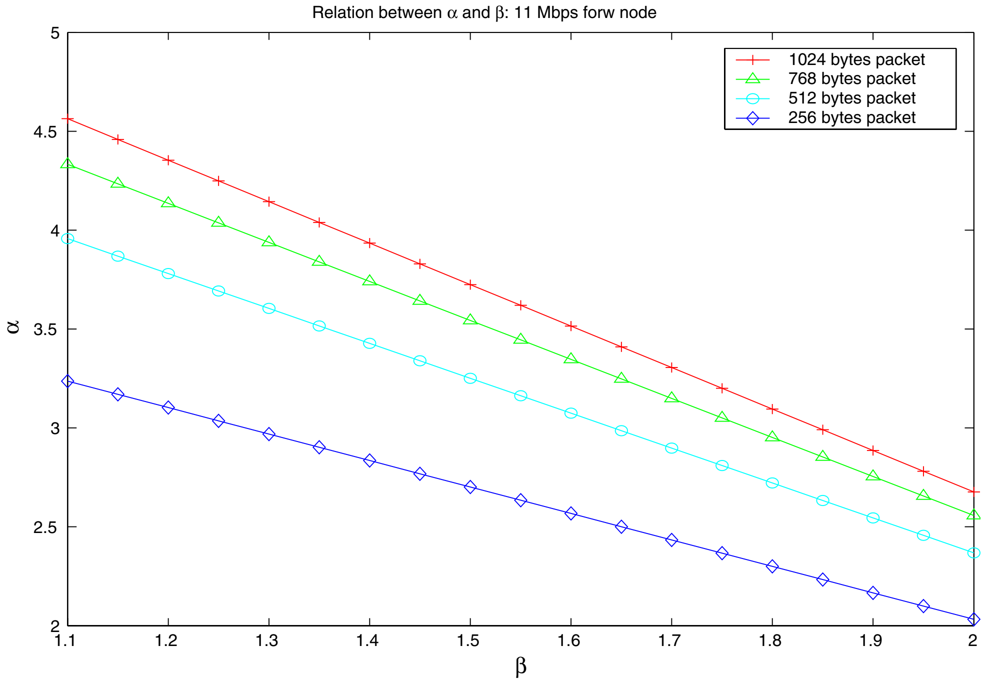

Figure 15. 11 Mbps forwarding node: α vs. β.

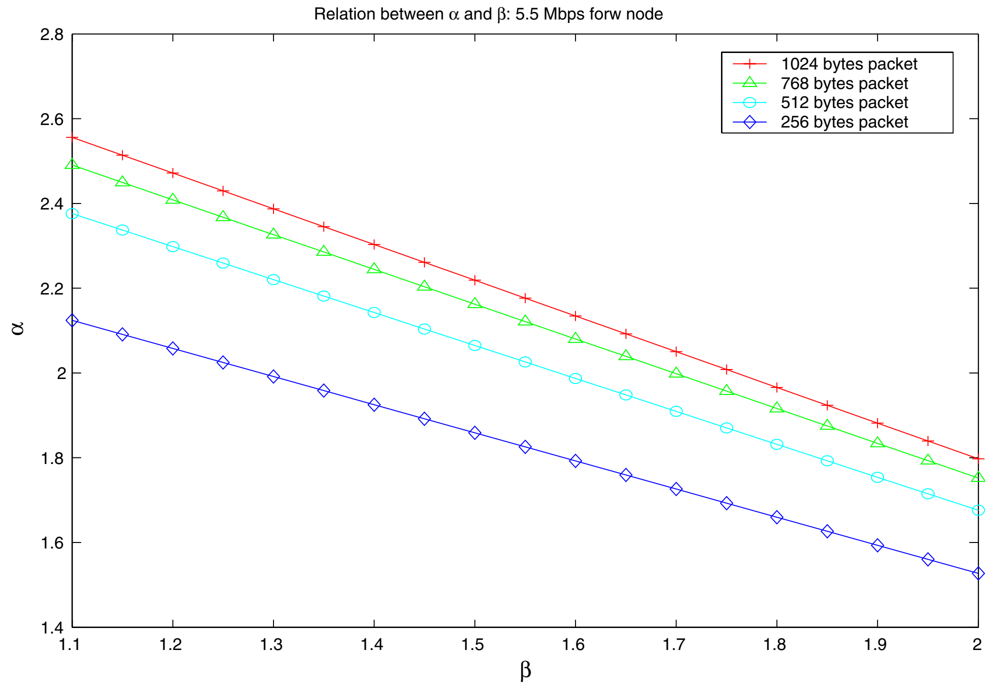

Figure 16. 5.5 Mbps forwarding node: α vs. β.

where f_1' and f_2' are the fractions of 1 Mbps nodes and 2 Mbps nodes that have a high-data rate forwarding node willing to assist with their respective transmissions [2]. Now, the total transmission time, receive time, and listen time for all the nodes in the network to transmit L bits are

$$\mathrm{TT}_{\mathrm{network}} = L/l * T_{\mathrm{MAC}},$$

$$\mathrm{TL}_{\mathrm{network}} = L/l * (N-1) * T_{\mathrm{MAC}}$$

and

$$\mathrm{TR}_{\mathrm{network}} = L/l * N * \mathrm{Backoff}.$$

Similarly, the total transmission time, receive time, and listen time for all the nodes in the network when high-data rate nodes participate in forwarding are

$$\mathrm{TT}^{\mathrm{Hop}}_{\mathrm{network}} = L/l * T^{\mathrm{Hop}}_{\mathrm{MAC}},$$

$$\mathrm{TL}^{\mathrm{Hop}}_{\mathrm{network}} = L/l * (N-1) * T^{\mathrm{Hop}}_{\mathrm{MAC}}$$

and

$$\mathrm{TR}^{\mathrm{Hop}}_{\mathrm{network}} = L/l * \left(N * \mathrm{Backoff} + \frac{T_{\mathrm{hop}}}{2}\right).$$

T_{hop}, derived in [2], captures the time spent in two-hop transmissions and on an average the reception time at forwarding nodes is half this time. Substituting $\mathrm{TT}_{\mathrm{network}}$, $\mathrm{TL}_{\mathrm{network}}$, and $\mathrm{TR}_{\mathrm{network}}$ in equation (2) for T_{T}, T_{L}, and T_{R}, respectively, the total energy consumption of

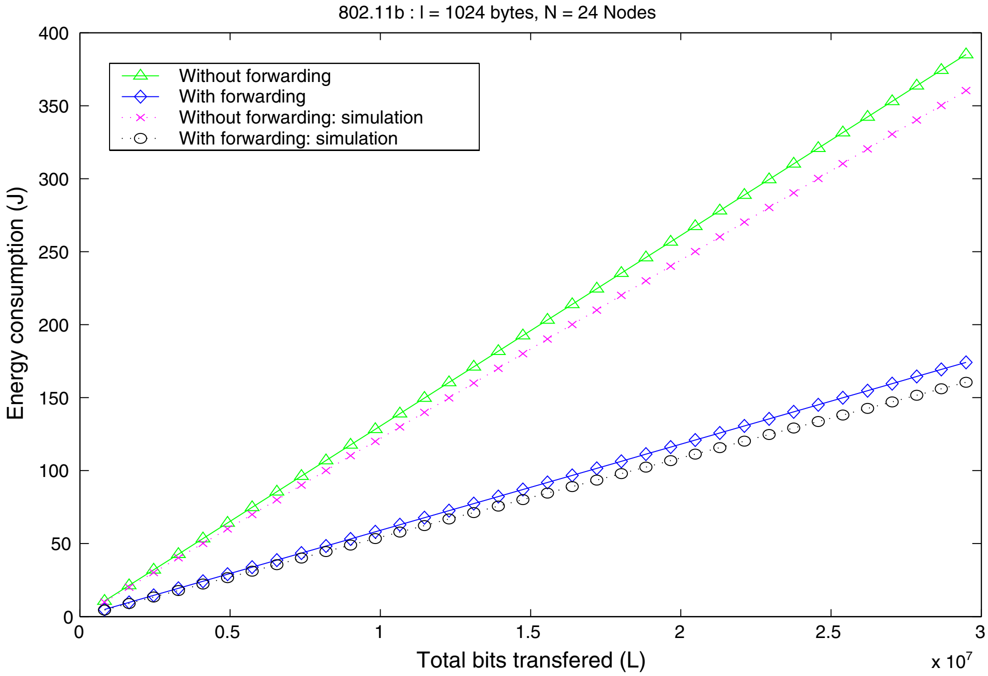

Figure 17. 802.11b: Total network energy consumption.

the network without two-hop forwarding can be calculated. Similar substitution of $TT^{Hop}_{network}$, $TL^{Hop}_{network}$, and $TR^{Hop}_{network}$ will give us the energy consumption when two-hop forwarding is used. The energy consumption for the whole network is shown in Figure 17. The difference in the energy consumption with and without forwarding is shown in Figure 18. As expected, the total energy expenditure of the network for a given throughput is lower when forwarding is used. We also tabulate the bits-per-joule value for each packet length in Table 3.

6. Simulation

We used the event driven software developed by the authors of [3] to perform simulation studies of the scenarios discussed in this paper. For a given number of nodes, the nodes were randomly distributed within the network and a forwarding node of a particular data rate was selected. The throughput and media access delay experienced by the node if it does not forward traffic and when its does, were collected. The results from these simulations are shown in Figures 2–5. Similar statistics were also collected for different packet lengths in a 24 node network. These results are shown in Figures 6–9. The results basically validate the correctness of our analysis.

To verify our analysis of the energy consumption, we used the simulator to track the transmission time, receive time, and listen time. The result calculated by substituting these times in equation (2) is shown in the Figures 10–13 and in Figures 17 and 18. Similarly the transmission time, receive time and, listen time for all the nodes in the network were gathered in simulation runs and used to calculate the energy consumption of the entire network. These results are shown in Figures 17 and 18.

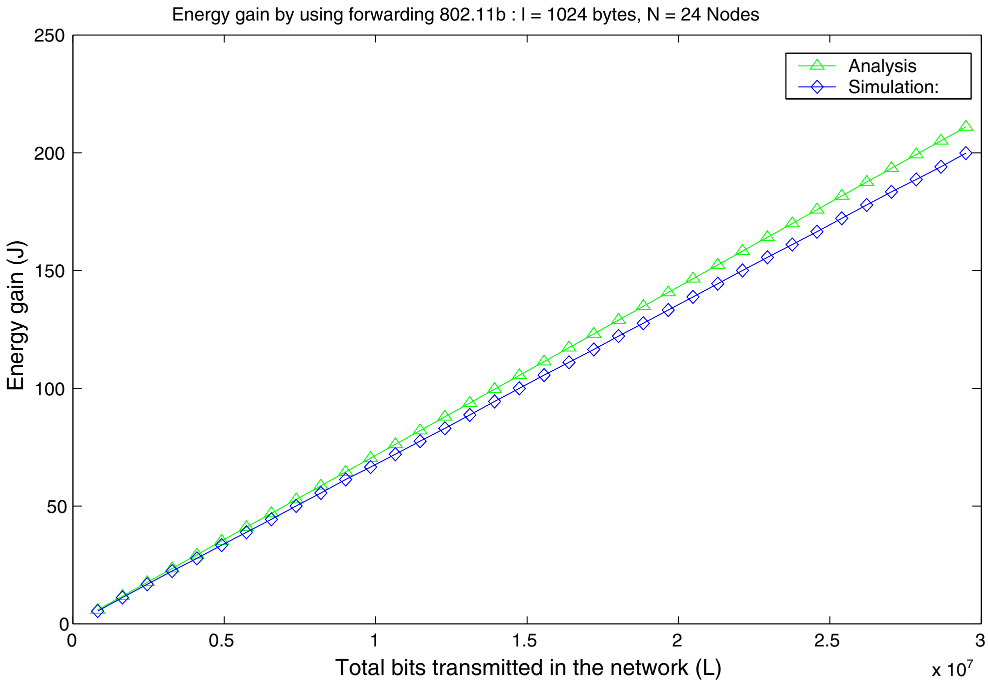

Figure 18. 802.11b: Total network energy gain.

Table 3. Bits-per-joule for 802.11b network

Packet length	W/o forw(x 10^4)b	With forw(x 10^4)b
1024 bytes	7.6576	16.937
768 bytes	7.4604	15.961
512 bytes	7.0948	14.311
256 bytes	6.1855	10.925

7. Forwarding Choice

For a node at a given data rate X, with a number of nodes in the network N, and a given estimate of the distance r from the access point, the expected throughput improvement and delay improvement can be calculated using the expressions derived in this paper. The choice of participating could be made dynamically based on a table look-up based on the results of such calculations. Since on the average there is an improvement over the lifetime of a device, a simpler design choice would be to always participate in forwarding.

It is important to note that if a node chooses to assist low-data rate nodes, the benefit in terms of throughput, delay, and energy consumption, is shared by all the nodes in the network. This is due to the long-term fairness property inherent in the 802.11 MAC design. Therefore, for two high-data rate nodes located very close to each other, if either one of the nodes participates in the scheme, the other will also receive the benefits without having to expend any of its energy. But, by choosing not to co-operate the device could be losing the significant benefits demonstrated in the paper because it may not know whether another high-data rate node is participating in forwarding. Since the energy consumption without forwarding grows larger over time, the best choice for each node in its own interest is to participate in forwarding irrespective of whether or not there are other nodes in the network that participate in such forwarding or not. Due to the advantages/results demonstrated in this paper, we claim that adopting two-hop forwarding in 802.11 nodes leads to a win–win situation for all the nodes in the network.

8. Conclusions

Using both analysis and simulation we have demonstrated that in an 802.11 network, providing assistance to low-data rate nodes by forwarding their data traffic, as suggested in Section 7, is beneficial for high-data rate nodes. As expected, we achieve benefits in terms of throughput and media access delay. Surprisingly, we also show a reduction in the long-term energy consumption of such a forwarding node. Based on these findings, the debate over whether or not to forward, and the question as to why a node would forward another node's traffic, can be settled with an affirmative answer. In an 802.11 network, there is no real or opportunity cost for nodes in forwarding traffic and a benefit is always gained. The opportunity cost is avoided by the specific design choice to allow for forwarding to happen immediately after a SIFS interval without requiring the forwarding node to go through a contention resolution procedure. The benefits shown in this paper demonstrates that incremental deployment of forwarding in 802.11 nodes is possible as long as the required modifications to the MAC protocol maintain backward compatibility with legacy 802.11 MAC protocol. With the design of such a backward compatible protocol, as presented in [3], incremental deployment can be realized.

References

1. Sathya Narayanan, Pei Liu, and Shivendra Panwar, "On the advantages of multi-hop extensions to IEEE 802.11 infrastructure mode", *Proc. of IEEE WCNC'05*, March 2005.
2. Sathya Narayanan, and Shivendra Panwar, "When two-hop meets VoFi", *Proc. of CCNC 2006*, January 2006.
3. P. Liu, Z. Tao, and S. Panwar, "A cooperative MAC protocol for wireless local area networks", *Proc. of IEEE ICC'05*, June 2005.
4. P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. Panwar, "CoopMAC: A cooperative MAC for wireless LANs", to appear in *IEEE Journal on Selected Areas in Communications*, special issue on *Cooperative Communications and Networking*.
5. Sathya Narayanan, Pei Liu, and Shivendra Panwar, "On the advantages of multi-hop extensions to IEEE 802.11 infrastructure mode", *New York Metro Area Networking Workshop*, September 2004.
6. H. Zhu and G. Cao, "rDCF: A Relay-enabled Medium Access Control Protocol for Wireless Ad Hoc Networks", *Proc. of IEEE Infocom*, March 2005.
7. Omer Ileri, Siun-Chuon Mau, and Narayan B. Mandayam, "Pricing for enabling forwarding in self-configuring ad hoc networks", *IEEE Journal on Selected Areas in Communications*, Vol. 23, No. 1, January 2005.
8. IEEE 802.11, "Wireless LAN Medium Access Control (MAC) and Physical layer (PHY) Specifications", Standard, *IEEE*, Aug 1999.
9. IEEE 802.11b, Part 11: "Wireless LAN Medium Access Control (MAC) and Physical layer (PHY) specifications: High-Speed Physical layer Extension in the 2.4 GHz Band", supplement to IEEE 802.11 Standard, Sept. 1999.
10. IEEE 802.11g, Part 11: "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications", Amendment 4: Further Higher-Speed Physical Layer Extension in the 2.4 GHz Band, June 2003.

11. Giuseppe Bianchi, "Performance analysis of the IEEE 802.11 Distributed Coordination Function", *IEEE Journal on Selected Areas in Communications*, Vol.18, No.3, March 2000.
12. Martin Heusse, Franck Rousseau, Gilles Berger-Sabbatel, and Andrzej Duda, "Performance anomaly of 802.11b" *Proc. of IEEE INFOCOM'03*.
13. P. Chatzimisios, A.C. Boucouvalas, and V. Vitsas, "IEEE 802.11 Packet delay–A finite retry limit analysis", *Proc. of IEEE Globecom'03*, December 2003.
14. Marcelo M. Carvalho, Cintia B. Margi, Katia Obraczka, and J.J. Garcia-Luna-Aceves, "Modeling energy consumption in single-hop IEEE 802.11 Ad Hoc Networks", *Proc. of ICCCN'04*, October 2004.
15. Ramesh Karri, and Piyush Mishra, "Optimizing IPSEC for energy efficient secure wireless sessions", *WICAT Technical report - TR-02-003*, Polytechnic University, April 2002.
16. L.M. Feeney and M. Nilsson, "Investigating the energy consumption of a wireless network interface in an ad hoc networking environment", *Proc. of IEEE INFOCOM'01*, April 2001.

Sathya Narayanan received his M.C.A from College of Engineering, Guindy, India, in 1994, M.S. in Computer Science from Temple University, Philadelphia, in 1998, and the Ph.D. degree in Computer Science from Polytechnic University, Brooklyn, NY, in 2006. He has over 10 years of industrial experience in both research and development of networking technologies. He was involved in the development and maintenance of a variety of commmunication products at Hughes Software Systems, New Delhi, India and Technical Communications Corporation, Concord, MA, as a senior software engineer during 1994 to 1997. Since 1999, he has been employed by Panasonic Princeton Laboratory at Princeton, NJ, where he currently holds a senior scientist position. His research interests are 802.11 MAC, co-operative communications, IPv6 mobility, Voice over IP, and peer-to-peer networking. He is active in IETF working groups related to IPv6 mobility and has co-authored various internet-drafts. He was a contributing engineer to CableLabs ® and has written acceptance test plans for DOCSIS1.1 standard.

Shivendra S. Panwar is a Professor in the Electrical and Computer Engineering Department at Polytechnic University. He received the B.Tech. degree in electrical engineering from the Indian Institute of Technology, Kanpur, in 1981, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Massachusetts, Amherst, in 1983 and 1986, respectively. He joined the Department of Electrical Engineering at the Polytechnic Institute of New York, Brooklyn (now Polytechnic University) in 1985. He is currently the Director of the New York State Center for Advanced Technology in Telecommunications (CATT). He spent the summer of 1987 as a Visiting Scientist at the IBM T.J. Watson Research Center, Yorktown Heights, NY, and has been a Consultant to AT&T Bell Laboratories, Holmdel, NJ. His research interests include performance analysis and design of networks. Current work includes video systems over peer-to-peer networks, switch performance, and wireless networks.

Dr. Panwar has served as the Secretary of the Technical Affairs Council of the IEEE Communications Society ('92–'93) and is a member of the Technical Committee on Computer Communications. He is a co-editor of two books, *Network Management and Control, Vol. II,* and *Multimedia Communications and Video Coding,* 1994 and 1996, respectively, both published by Plenum, and co-authored a textbook, *TCP/IP Essentials: A Lab-Based Approach,* Cambridge University Press, 2004. He is a co-recipient of the 2004 *IEEE Communications Society Leonard G. Abraham Prize in the Field of Communications Systems.*