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When two-hop meets VoFi

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Abstract—**In a paper titled *Can I add a VoIP call?*[1], the authors calculate the maximum number of VoIP calls that a WiFi (VoFi) network can support. In this paper we extend their analysis to calculate the maximum number of VoFi calls when two-hop forwarding is used in order to avoid rate adaptation at nodes with reduced received signal strength. We calculate this number for different combinations of data rates for slow node transmissions and potential two-hop transmissions. These calculations demonstrate that the use of two-hop forwarding increases the maximum number of VoIP calls in a multi-rate 802.11b network. We validate the analysis by means of simulation of G711 codec sources in a 802.11b network. Even though the earlier discussions focus on specific combinations of high data rate two-hop and low data rate one-hop transmissions in an 802.11b network, we conclude the paper by calculating the maximum number of VoIP calls that can be supported with uniform node distribution in 802.11b and 802.11g networks. These calculations show a significant increase in the number of VoIP calls when two-hop forwarding is used in an 802.11g network. This significant increase is due to the higher data rates and the low PHY overhead of the 802.11g MAC.**

Keywords— **IEEE 802.11, Voice Over IP, VoIP, VoFi, MAC, Wireless LANs, Link adaptation, multi-hop forwarding.**

I. Introduction

In [1] the authors argue that the capacity of the 802.11b is the dominant restricting factor in carrying VoIP traffic. As is well-known, 802.11b supports four different data rates and the wireless nodes adapt their data rates based on their received signal strength. We proposed the use of two-hop forwarding in our earlier work [2][3], thus reducing the use of low data rates and demonstrating the resulting throughput improvements of such two-hop forwarding. In this paper we consider the application of two-hop forwarding to VoIP traffic in the DCF mode and analyze the performance benefits.

A. Related work

[1] derives an expression for the maximum number of VoIP calls that can be supported in 802.11 DCF mode and argues that this number is constrained by the capacity of the network. *VoIP calls* in this discussion (and for the rest of the paper) refer to VoIP end-points, rather than actual VoIP calls. These two values are equal only if all the end-points have their counterpart outside the 802.11 network. For consistency, in the rest of this paper we will refer to the number of VoIP active nodes in the 802.11 network as VoFi end-points. [6] argues that the PCF mode of 802.11 is better suited for VoFi calls and presents an architecture for such deployment. [4] presents simulation results for carrying VoIP traffic on 802.11b network with the quality of the call being measured by the E-model recommended in ITU G.107.

II. Average data transmission rate

The IEEE 802.11 standard has defined multiple data rates and allows each wireless node to select an appropriate data rate based on its signal strength. In the case of 802.11b, a node could be transmitting at 11 Mbps, 5.5 Mbps, 2 Mbps or 1 Mbps based on its signal strength. The average data transmission rate for the network depends on these individual data rates. Let N_X be the number of nodes transmitting at transmission rate X Mbps, where X is 11, 5.5, 2, or 1 and N be the total number of nodes in the network. The fraction of nodes transmitting at rate X, f_X, is given by $\frac{N_X}{N}$. When all the nodes in the network are generating the same traffic load, the average bit transmission time T_{Avg} in the network can be expressed as $\sum_X \frac{f_X}{X}$, and the average data transmission rate R_{Avg} is the reciprocal of T_{Avg}, as shown below,

$$R_{Avg} = \frac{1}{\sum_X \frac{f_X}{X}}$$

A. Two hop forwarding

As presented in [2] and [3], the use of two-hop transmission at higher rates to reach the destination is likely to increase the average transmission rate of the network. A node which can maintain a lower data rate link to its destination, referred to as a slow node, chooses an intermediary node, referred to as a forwarding node, and transmits data to the destination using two high rate transmissions through the forwarding node. We recommend that the forwarding node avoid the overhead of contention resolution and forward the packets to the final destination a SIFS interval after the packet is received. We also recommend that the acknowledgment for the packet be sent from the destination of the packet directly to the source at the lower rate of the source in order to avoid the physical layer overhead for an additional ACK transmission. Throughout this paper, we assume that the only active nodes in the network are the ones with active VoIP calls.

With the use of two-hop forwarding the average bit transmission T_{Avg}^{Hop} time is the sum of the average bit transmission times using direct transmission and two-hop transmission. $T_{Avg}^{Hop} = T_{nohop} + T_{hop}$ where T_{nohop} is the contribution by the direct transmissions to the average time, while T_{hop} is the contribution by two-hop transmissions to the average time.

T_{hop} is constructed from four components:

- Fraction of nodes at 2 Mbps and at 1 Mbps that can find a forwarding node to forward its traffic with two 11 Mbps hops . We denote these fractions by f_2^{1111} and f_1^{1111} respectively.
- Fraction of nodes at 2 Mbps and at 1 Mbps that can find a forwarding node to forward its traffic with two 5.5 Mbps hops. We denote these fractions by f_2^{5555} and f_1^{5555} respectively.
- Fraction of nodes at 2 Mbps and at 1 Mbps that can find a forwarding node to forward its traffic with one 11 Mbps and one 5.5 Mbps hop. We denote these fractions by f_2^{1155} and f_1^{1155} respectively.
- Fraction of nodes at at 1 Mbps that can find a forwarding node to forward its traffic with one 11 Mbps or one 5.5 Mbps along with one 2 Mbps hop. We denote these fractions by f_1^{112} and f_1^{552} respectively.

$$\begin{aligned} T_{hop} &= 2\cdot((f_2^{1111} + f_1^{1111})\cdot\frac{1}{11} + (f_2^{5555} + f_1^{5555})\cdot\frac{1}{5.5}) \\ &+ (f_2^{1155} + f_1^{1155})\cdot(\frac{1}{11} + \frac{1}{5.5}) + f_1^{112}\cdot(\frac{1}{11} + \frac{1}{2}) \\ &+ f_1^{552}\cdot(\frac{1}{5.5} + \frac{1}{2}) \end{aligned}$$

The multiplication by 2 is done to count the transmission time both at the source node and the forwarding node.

T_{nohop} is constructed from the following three components:

- Nodes that are at 11 Mbps and nodes that are at 5.5 Mbps. The 5.5 nodes need not use two hop forwarding as the sum of the times taken for the two transmissions at 11 Mbps will be more than the direct transmission time due to the additional PHY overhead.
- Fraction of nodes at 2 Mbps that cannot find a node to forward its traffic. This fraction is $f_2 - f_2'$ where $f_2' = f_2^{1111} + f_2^{5555} + f_2^{1155}$. f_2' denotes the fraction of 2 Mbps nodes that has a high data rate forwarding node willing to assist its transmissions.
- Fraction of nodes at 1 Mbps that cannot find a node to forward its traffic. We do not consider using a node at 2 Mbps as a forwarding node for the same reason given above. This fraction is $f_1 - f_1'$ where $f_1' = f_1^{1111} + f_1^{5555} + f_1^{1155} + f_1^{112} + f_1^{552}$. f_1' denotes the fraction of 1 Mbps nodes that have a high data rate forwarding node willing to assist its transmissions.

$$T_{nohop} = \frac{f_{11}}{11} + \frac{f_{5.5}}{5.5} + \frac{f_2 - f_2'}{2} + \frac{f_1 - f_1'}{1}$$

Using two-hop forwarding, the transmission rate R_{Avg}^{Hop} is the reciprocal of T_{Avg}^{Hop}. Figures 1 through 4 plot the average transmission rate experienced with and without two hop forwarding for four combinations of (data rate of both hops, slow node data rate); namely (11,1), (11,2),(5.5,1),(5.5,2). The fraction of nodes (f_{11}, $f_{5.5}$, f_2, f_1) for each of the graph is ($\frac{N-x}{N}$, 0, 0, $\frac{x}{N}$), ($\frac{N-x}{N}$, 0, $\frac{x}{N}$, 0), ($\frac{N-x}{N}$, 0, 0, $\frac{x}{N}$), ($\frac{N-x}{N}$, 0, $\frac{x}{N}$, 0) respectively, where x is the value on the X-axis. These scenarios were chosen to demonstrate the advantage of two-hops and provide comparison between the data rates used for two-hops. We present the average case calculations in Section IV.

III. Number of VoFi end-points

Due to the high packet overhead introduced by RTP/UDP/IP and the MAC/PHY layers of 802.11, the maximum number of the VoFi end-points is severely restricted by the capacity of the 802.11 network [1]. We begin with the expression for the maximum number of VoFi end-points n_{max}, as derived in [1]:

$$\lfloor \frac{R_{Avg}}{2\cdot V_{rate}} \cdot \frac{T_p}{(T_p + T_{layers} + T_{P+D+S+A} + T_{dcf})} \rfloor \quad (1)$$

where the first factor is the number of VoFi end-points of a given vocoder rate (V_{rate}) that can be squeezed in a given data rate channel (R_{Avg}), while the second factor

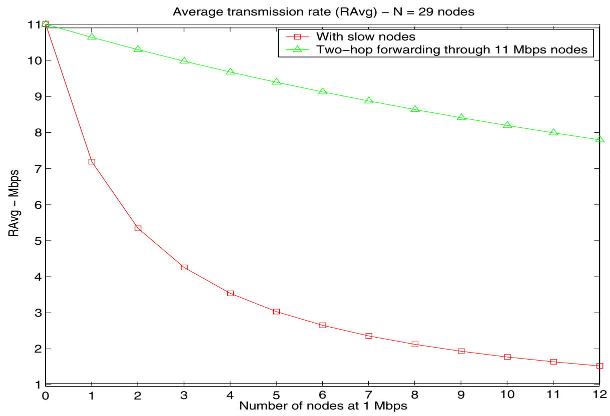

Fig. 1. Forwarding data rate 11 Mbps/Slow nodes 1 Mbps

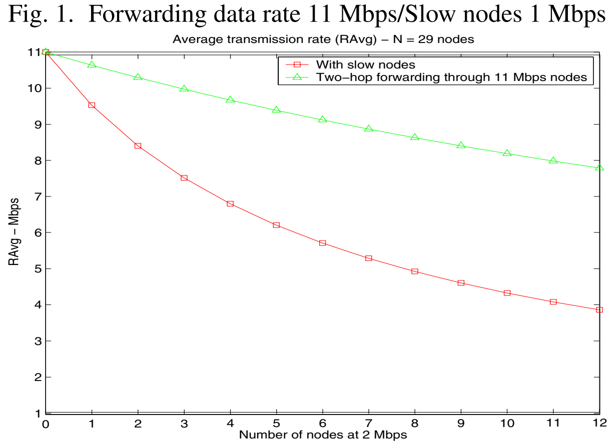

Fig. 2. Forwarding data rate 11 Mbps/Slow nodes 2 Mbps

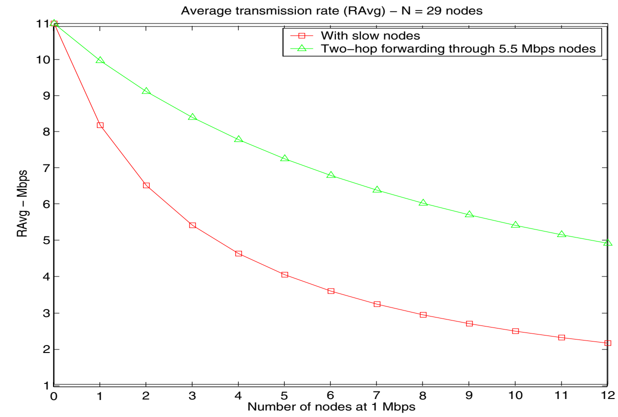

Fig. 3. Forwarding data rate 5.5 Mbps/Slow nodes 1 Mbps

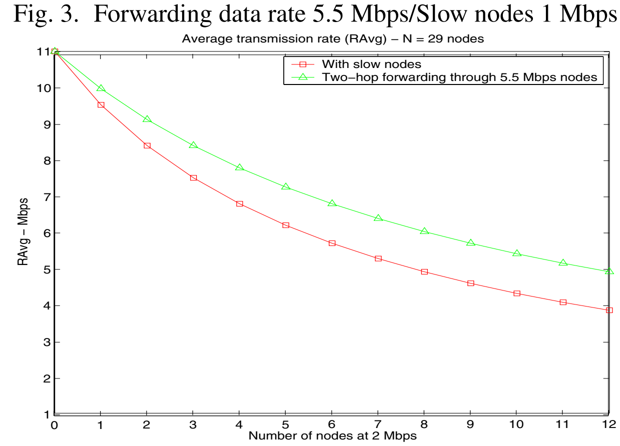

Fig. 4. Forwarding data rate 5.5 Mbps/Slow nodes 2 Mbps

is the maximum channel efficiency ($ChannelEff$). The channel efficiency ($ChannelEff$) is calculated as a ratio of time taken for transmitting the actual voice payload to the time spent on the actual payload plus the related overhead. T_p is the time taken to transmit the voice payload of P bytes ($T_p = \frac{P}{R_{Avg}}$), T_{layers} is the time to transmit the RTP, UDP, IP, and MAC layer headers ($T_{layers} = \frac{P_{layers}}{R_{Avg}}$, where $P_{layers} = 74bytes$), $T_{P+D+S+A}$ is the sum of PHY, DIFS, SIFS and ACK time, and T_{dcf} is the time delay introduced by the contention resolution algorithm for each transmission. In [1], the value for T_{dcf} is calculated under the assumption that only two nodes, one wireless node and the access point, will contend for the channel at the same time. The periods of silence in a voice conversation are ignored and bi-directional transmission at the full vocoder rate is assumed in [1]. We refer to this case as the CBR case. For conversational speech, [5] recommends a ON/OFF model with mean ON duration 1.0s, and mean OFF duration 1.35s, both following the exponential distribution. Voice activity using this model is 42.6%, and therefore V_{rate} will be 42.6% of the CBR data rate. We refer to this case as the VBR (Variable Bit Rate) case.

A. CBR case

An increase in the average transmission rate was demonstrated in section II. Does this increase translate to an increase in the number of VoFi end points? The answer depends on how the overhead introduced by two-hop forwarding compares to the increase gained in the average transmission rate as a result of such forwarding. In order to calculate the maximum number of VoFi calls using two-hop forwarding, we need to calculate the maximum channel efficiency when two hop forwarding is used ($ChannelEff_{Hop}$). $ChannelEff_{Hop}$ is given by

$$\frac{T_p^{Hop}}{(T_p^{Hop} + T_{layers}^{Hop} + T_{P+D+S+A} + T_{dcf} + T_{overhead}^{Hop})}$$

where T_p^{Hop} and T_{layers}^{Hop} are the time to transmit the payload and upper layer headers, respectively using two hop forwarding. Also, along with the physical layer and contention overhead, the two-hop overhead denoted by $T_{overhead}^{Hop}$ must also be taken into consideration. $T_p^{Hop} = \frac{P}{R_{Avg}^{Hop}}$, and $T_{layers}^{Hop} = \frac{P_{layers}}{R_{Avg}^{Hop}}$, where P is the size of the voice packets from the codec and P_{layers} is the size of

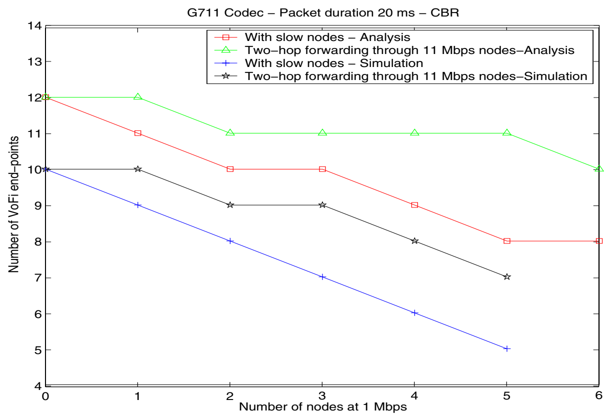

Fig. 5. Forwarding data rate 11 Mbps/Slow nodes 1 Mbps

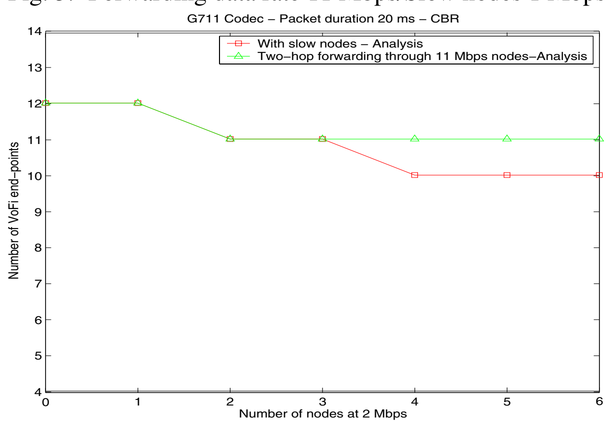

Fig. 6. Forwarding data rate 11 Mbps/Slow nodes 2 Mbps

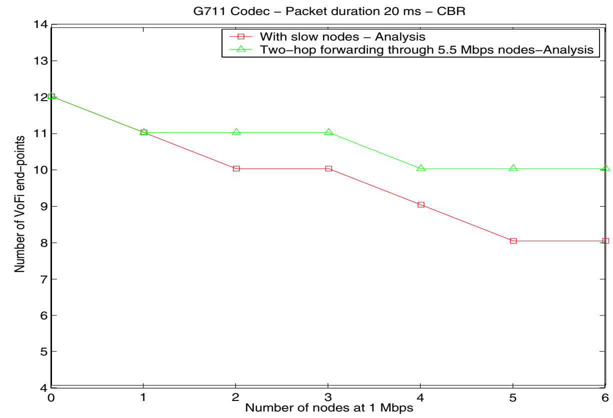

Fig. 7. Forwarding data rate 5.5 Mbps/Slow nodes 1 Mbps

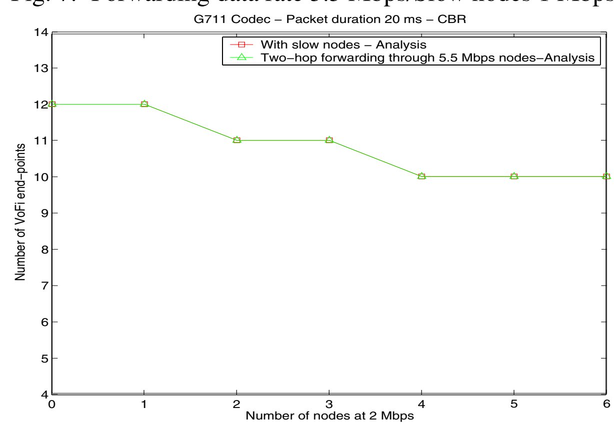

Fig. 8. Forwarding data rate 5.5 Mbps/Slow nodes 2 Mbps

the overhead added by lower layers on the voice packet. The maximum number of VoFi endpoints with two hop forwarding is

$$\lfloor \frac{R_{Avg}^{Hop}}{2 \cdot V_{rate}} \cdot ChannelEff_{Hop} \rfloor$$

We calculate the value for T_{dcf} in a manner similar to [1]. The overhead involved in a two-hop transmission includes one SIFS interval and a PHY overhead. Hence

$$T_{overhead}^{Hop} = (T_S + T_P) * (f_1' + f_2')$$

The first factor in the overhead is SIFS intervals for the opportunistic access by the forwarding node, the second being the additional PHY overhead for the second transmission. Comparisons of the maximum number of VoFi end-points with and without two-hop forwarding for CBR case are shown in figures 5 through 8 for the same four combinations of (data rate of both hops, slow node data rate). Even though the simulation result shown in Fig.5 has a similar shape as the analysis, there is a difference in the actual values. We believe this difference is primarily due to a higher collision probability found in the simulation.

B. VBR case

As demonstrated in [1] and by our own calculations, we note that the maximum number of VoFi end-points in the CBR case is constrained by the capacity of the wireless network. In the VBR case, with the average vocoder rate at 42.6% of the CBR case, the total number of VoFi end-points that can be supported by the capacity of the network increases significantly. But this increase is not realizable as the average end-to-end delay experienced by the voice calls becomes the dominant constraining factor on this number. Given the probability that a sending node is active, p (= 0.426), the number of calls n_{vbr} that can be multiplexed, in a network that can support n_{max} CBR calls, while maintaining a loss rate less than ε is shown in [6] to be:

$$\frac{1}{2pn_{vbr}} \sum_{k=2n_{max}+1}^{2n_{vbr}} (k - 2n_{max})(2n_{vbr}C_k)P(k) \leq \varepsilon$$

where $P(k) = p^k(1-p)^{2n_{vbr}-k}$
and $2n_{vbr}C_k$ is the combination of $2n_{vbr}$ taken k at a time.

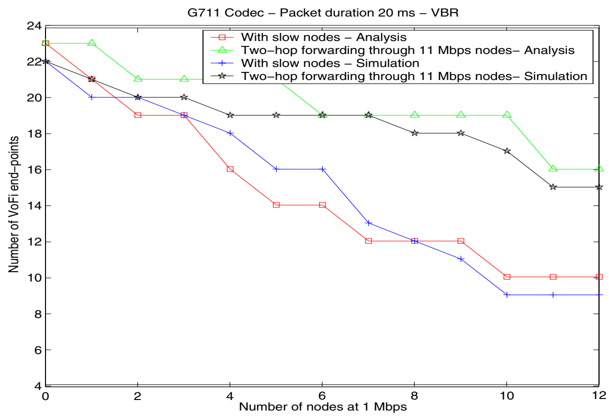

Fig. 9. Forwarding data rate 11 Mbps/Slow nodes 1 Mbps

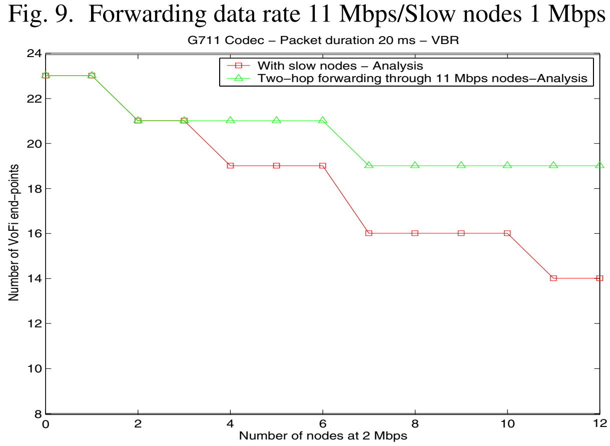

Fig. 10. Forwarding data rate 11 Mbps/Slow nodes 2 Mbps

TABLE I
NUMBER OF VOIP END POINTS - 802.11B

CODEC	GSM6.10	G723.1	G726-32	G711
Payload(bytes)	33	20	80	160
Interval(ms)	20	30	20	20
CBR-With slow	8	13	7	5
CBR-Two-hop	10	15	9	7
VBR-With slow	14	25	12	8
VBR-Two-hop	19	30	16	12

The results from our calculation for the VBR case (with $\varepsilon = 0.01$) are shown in figures 9 through 12. The number of VoFi end-points (Y-axis of the figures) identify the total number of nodes with active VoIP call in the network.

IV. UNIFORM DISTRIBUTION OF NODES

A. IEEE 802.11b

Assuming uniform distribution of the nodes in the network, the fraction of nodes at a particular rate can be calculated as the ratio of the areas of concentric circles [3].

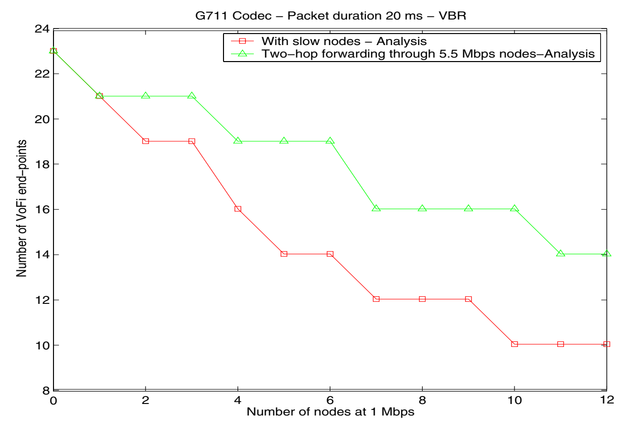

Fig. 11. Forwarding data rate 5.5 Mbps/Slow nodes 1 Mbps

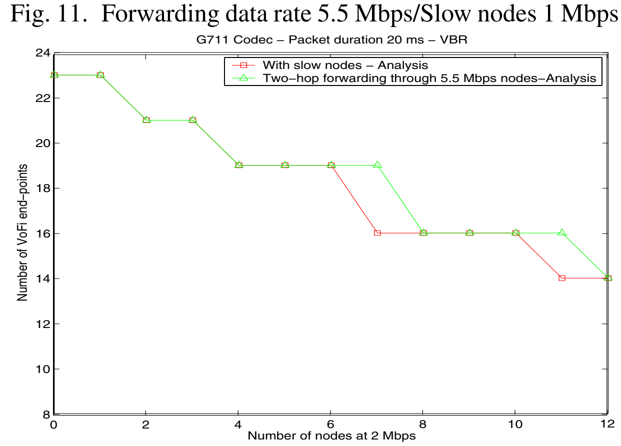

Fig. 12. Forwarding data rate 5.5 Mbps/Slow nodes 2 Mbps

TABLE II
NUMBER OF VOIP END POINTS - 802.11G

CODEC	GSM6.10	G723.1	G726-32	G711
Payload(bytes)	33	20	80	160
Interval(ms)	20	30	20	20
CBR-With slow	12	19	10	7
CBR-Two-hop	16	26	14	11
VBR-With slow	23	39	19	12
VBR-Two-hop	32	55	27	21

Based on the analysis presented in [3] the probability of finding a particular data rate two hop transmission can also be calculated for the nodes at rate 2 Mbps and 1 Mbps. Using these probabilities, the maximum number of VoFi end-points for well known codecs are shown in Table I.

B. IEEE 802.11g

Considering the mandatory rates of 802.11g (1,2,6,12, and 24 Mbps), the fraction of nodes at various data rates can be calculated similarly based on the fraction of areas of the concentric circles. Repeating the calculations from [3]

TABLE III
MAC CONSTANTS

Constants	Values
CW MIN (802.11b)	32
SIFS	10 μs
DIFS	50 μs
PHY (802.11b)	192 μs
PHY (802.11g)	52 μs

for these data rates, we present the average case results in Table II. A higher relative increase in the number of end-points is experienced in the case of 802.11g as the two-hop overhead added due to the PHY layer is significantly smaller (refer to Table III).

We show the maximum number of VoIP end-points that can be supported by an 802.11g access point when a mix of 802.11g and 802.11b nodes are present in the network in Fig.13. As the fraction of 802.11g nodes in the network increases, the number of VoIP end-points stays almost flat using current MAC due to the presence of 802.11b and slower 802.11g nodes. These calculations were based on the probability of using a higher rate hop when an 802.11g node is the source while using the lower 802.11b data rate when a 802.11b node is the source. As can be seen in Fig.13, using two-hop forwarding has a significant advantage as more 802.11g nodes are added to the network. Since this improvement is achieved without including the optional data rates (36, 48 and 54 Mbps) of 802.11g, its reasonable to expect even better improvements when the optional data rates are taken into account.

V. SIMULATION

We conducted simulation experiments of VoIP traffic on 802.11b network using the G711 codec rates as the source rates in the OPNET [7] simulation tool. The simulations were done for both CBR and VBR cases with slow nodes at 1 Mbps and forwarding nodes at 11 Mbps. The network consists of 802.11 nodes randomly located around the access point at the center. The voice data is transmitted between these nodes with each VoFi end-point being a source for voice data addressed to another pre-configured node within the network. Even though there were more nodes (33) in the network, only the active nodes participate in forwarding, i.e. the nodes without an active VoIP call do not affect the network in anyway for the particular simulation run. In the CBR case, the maximum number of VoFi end-points supported by the simulation is shown in Fig.5. When one VoFi end-point more than the maximum shown in Fig.5 is added to the simulation, the end-to-end delay

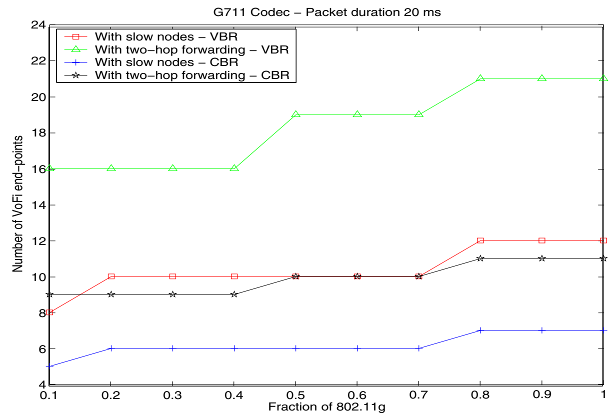

Fig. 13. 802.11g - 802.11b co-existence

grows steadily, indicating that the capacity of the network has already been reached. Comparing the results from the analysis and simulation in Fig.5, we can see that the simulation results closely trace the expected values from the analysis. As mentioned in section III-A, we believe the difference between the analytical and simulation result is primarily due to the difference in the collision probability. For the VBR case, we used the ON/OFF model recommended by [5] for conversational speech. The simulation results are shown in Fig.9. This simulation result is based on the end-to-end delay being below 100 milli-seconds, i.e. when one more VoFi end-point is added to the simulation the average end-to-end delay of the calls increase above 100 milli-seconds. Again, the simulation results closely trace the analytical result.

VI. CONCLUSION

We demonstrated, through both analysis and simulation, that the maximum number of VoIP end-points supported by a 802.11 network can be increased if two-hop forwarding at higher rates is used instead of using rate adaptation to address signal quality.

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