Effect of Fading on the Performance of VoIP in IEEE 802.11a WLANs

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***Abstract*— We investigate the quality of voice communication over IEEE 802.11a WLANs taking realistic channel models into account. We show that the assessment of VoIP performance is overly optimistic if fading is ignored when compared with systems where fading is taken into account. Via simulation, we derive the distribution of VoIP performance (in terms of mean opinion score - MOS) for all the data rates specified in the IEEE 802.11a standard and a range of typical signal-to-noise ratio values. We use a measure for assessing VoIP performance that includes a target level of user-satisfaction and a bound on the probability of not achieving this target. The impact of retransmissions and channel estimation errors on VoIP performance is also discussed.**

I. Introduction

Wireless LANS (WLANs) are being used as an extension to cellular networks in hot-spots or areas with limited or no access to cellular networks to provide data services [1]. These networks can potentially be used for voice communication as an alternative to the current cellular voice technology [2].

Generally, research pertaining to VoIP over WLANs has been centered on the effects that packet delay and packet loss occurring at the MAC layer and higher layers have on VoIP performance. In most of these studies, errors in transmission over the wireless channel are either ignored or represented by simplified models which do not necessarily reflect realistic wireless environments [3],[4].

Wireless channels manifest signal variation in the form of path-loss, shadowing and small-scale fading. Path-loss is the distance-dependent attenuation in signal power. Shadowing is the large-scale variation in signal power due to large objects (objects with sizes larger than the wavelength) in the environment. Small-scale fading is the rapid variation in signal envelope due to the transmitted signal undergoing reflection(s) and scattering leading to multiples copies with different amplitudes, phases and delays summing up at the receiver [5]. We refer to small-scale fading in the sequel simply as fading.

There is prior literature on the performance of the physical layer of WLANs in realistic wireless channels, taking into account fading. In [6],[7],[8] the authors simulated the physical layers of HIPERLAN/2 and IEEE 802.11a systems (which are very similar) in fading channels using the ETSI channel models [9], and they obtained the average packet error rate (PER) by averaging over the channel fading realizations [6],[8]. Using the average PER, the impact of various ETSI channel models on the performance of these systems was studied. In [7] the average throughput for both systems, derived from the average PER, is used for link adaptation purposes.

Lampe et al. simulated the HIPERLAN/2 system using the ETSI channel models and showed that using average PER for link adaptation can lead to "fatal misadaption" [10]. Therefore, the authors proposed that the PER corresponding to the particular fading realization experienced should be used for link adaptation, and not the average.

In this paper, we study the impact of fading in the wireless channel on packet loss and the performance of VoIP over IEEE802.11a using a realistic channel model.

VoIP performance is measured in terms of the user-perceived quality over a speech period comprising a number of VoIP packets. When fading is constant over such duration, then the voice quality will depend on the PER incurred under that particular fading realization, and not the average PER. This situation arises if the pair of VoIP users are stationary during the time window over which the performance is measured.

In this paper, we consider VoIP users to be stationary and each user subject to a particular fading realization; this leads to a particular value for PER which in turn translates to a mean opinion score (MOS) value representing the voice quality for calls under that fading realization. By considering a large number of fading realizations, we derive a distribution for voice quality across users. This approach for studying VoIP performance is consistent with the approach taken in [10] for link adaptation in that one must take into consideration individual fading realizations when evaluating VoIP quality. It is in contrast with studies that base performance evaluation (and adaptation) on averaging over many channel fading realizations.

This paper is organized as follows: in section II, we present the system model. Numerical results for PER are discussed in section III, followed by the quality assessment of VoIP in section IV. Section V comprises the conclusion.

II. System Model

The system under consideration is an IEEE 802.11a basic service set (BSS) in which pairs of stationary VoIP devices are communicating. A pair of devices represents either 2 VoIP stations or a VoIP station and an access point (AP). Communication between one device and its partner experiences a particular fading realization which may be different from that experienced by another communicating pair in the BSS.

Restricting the traffic in the BSS to be only VoIP traffic (as would be the case if one were to consider the WLAN to be dedicated for VoIP application), the probability of collisions among VoIP packets is very small, even when the system is loaded to its capacity (see [4]); and can therefore be ignored. Furthermore, we also ignore any interference from users in neighboring BSS's. As a result, the only source of packet errors that we consider is that of the physical layer and the underlying wireless channel.

Consider two devices, one transmitting to the other. Let P_t denote the transmit power, G_t and G_r, the transmitter and receiver antenna gains, P_{loss} the loss due to path-loss and shadowing, and N_{power} the receiver noise power and Im the implementation margin. The signal-to-noise ratio in dB ignoring fading, $\widetilde{SNR}$ is given by

$$\widetilde{SNR} = P_t + G_t + G_r - P_{loss} - N_{power} - Im \quad (1)$$

A simplified version of the Keenan-Motley partition loss model that incorporates free-space model and shadowing in the environment [11] is used to determine P_{loss},

$$P_{loss} = P_{free-space}(d, \lambda) + a \cdot d \quad (2)$$

where $P_{free-space}(d, \lambda)$ is the free-space path-loss model which is a function of the distance d and the wavelength λ, and a is the additional power attenuation per meter. N_{power} is given by

$$N_{power} = 10log_{10}(K \cdot T \cdot B) + NF \quad (3)$$

where K is the Boltzmann constant, T is the temperature, B is the bandwidth and NF is the noise figure.

In the IEEE 802.11a standard [12], the maximum transmit power is 200 milliwatts for WLANs operating at a carrier frequency within the 5.25-5.35 GHz frequency range with a bandwidth (B) of 20 MHz. NF and Im are also specified in the standard to be 10 dB and 5 dB, respectively. Medbo et al. showed in [13] that Eqn. 2 adequately models the loss in a typical office environment at carrier frequency of 5 GHz for $a = 0.44$ dB/meter. To be on the conservative side, we assume both transmit and receive antenna gains to be 0 dBi. To calculate N_{power}, we consider $T = 290$ Kelvin. With these specific values for the various parameters, we get a correspondence between $\widetilde{SNR}$ and distance d, as shown in Table I.

TABLE I
DISTANCE

$\widetilde{\text{SNR}}$ (dB)	**5**	**10**	**15**	**20**	**25**	**30**	**35**
d (Meters)	52	44	36	28	23	17	12

To represent fading, we consider the ETSI indoor channel A delay profile with an RMS delay spread of 50 nanoseconds which models a typical office environment with no line-of-sight (NLOS) [9]. This delay profile results in frequency selective fading in the IEEE 802.11a 20 MHz band. Noise is modeled as additive white Gaussian noise (AWGN).

Speech data generated by the encoder is packetized incurring overheads at the various layers (transport, network and MAC layers). We consider G.711 which generates speech data at the rate of 64 Kbps, and consider each packet to contain 10 ms of speech, or 80 bytes of data. At the transport layer, the RTP and UDP protocols introduce 12 byte and UDP 8 byte headers, respectively. At the network layer, the IP protocol introduces a header of 20 bytes; and at the MAC layer the header is 34 bytes; the total overhead is then 74 bytes. Hence a 10 ms VoIP packet is 154 bytes long.

The quality of voice communication is affected by packet loss. Voice quality is measured by the mean opinion score (MOS); it is a measure ranging from 1 to 5 that represents the user-perceived voice quality at the receiving end. The relationship between MOS values and user satisfaction is shown in Fig. 1a. A MOS ≥ 4 is considered desirable while a MOS between 3.6 and 4 is considered acceptable.

A model standardized by the ITU-T called the Emodel relates quantities in the network such as packet loss rate and packet delay to MOS [14]. In Fig. 1b, we plot MOS vs. PER for G.711 with packet-loss error-concealment (PLC) which we consider in this paper.

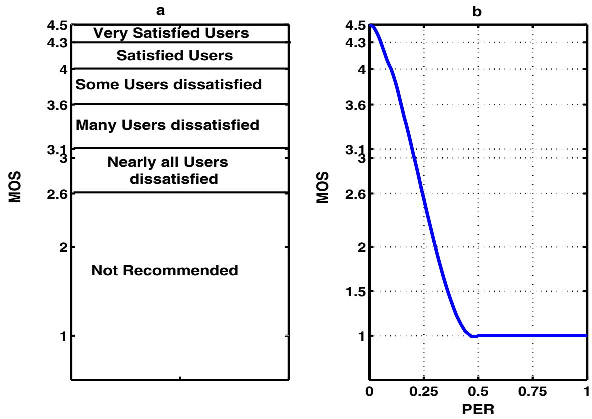

Fig. 1. **a. Relationship between MOS and User Satisfaction b. Relationship between MOS and PER for G.711 with PLC**

We built a simulation for the physical layer of IEEE 802.11a in a wireless channel with and without fading. We represented in the simulation the various stages of the transmitter and receiver; in the latter, we considered a hard-decision Viterbi decoder. We assumed perfect synchronization. For channel estimation, we consider scenarios with both perfect channel estimation and channel estimation based on the time domain least squares (TDLS) algorithm [15].

The channel model allows us to generate different fading realizations. For a given fading realization, we simulate 1000 fixed size packets (154 bytes long) and obtain a packet error rate (PER). We consider 1000 different channel fading realizations to obtain a distribution for PER at a given data rate and given $\widetilde{SNR}$. The results presented below correspond to perfect channel estimation. We do however examine in section IV the effect of estimating the channel based on TDLS.

III. PER Results

To illustrate the importance of fading on packet errors, consider the 24 Mbps data rate and $\widetilde{SNR}$ = 15 and 20 dB. We find via simulation that for a channel with no fading, PER = 0 for both $\widetilde{SNR}$ values. However, with fading, we obtain the histogram shown in Fig. 2. We find that PER is distributed between 0 and 1 with PER_{ave} = 0.4 and 0.07 for $\widetilde{SNR}$ = 15 dB and 20 dB, respectively. We also find that the percentage of realizations with PER $>$ PER_{ave} is 41% and 14% for $\widetilde{SNR}$ = 15 dB and 20 dB, respectively.

Most of the results in the remaining part of this section will be presented using complementary cumulative distribution functions (CCDFs); that is Pr$\{PER > X\}$. This allows one to examine system performance in terms of Pr$\{PER > X\}$ for a desirable X dictated by the applications, and find the system conditions under which this probability is below a certain acceptable threshold.

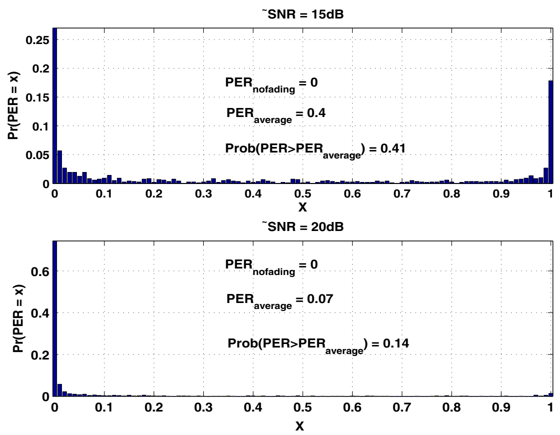

Fig. 2. **Histograms of PER for 24Mbps at $\widetilde{SNR}$ = 15 & 20 dB**

We plot in Fig. 3 the CCDF for PER for 24 Mbps and

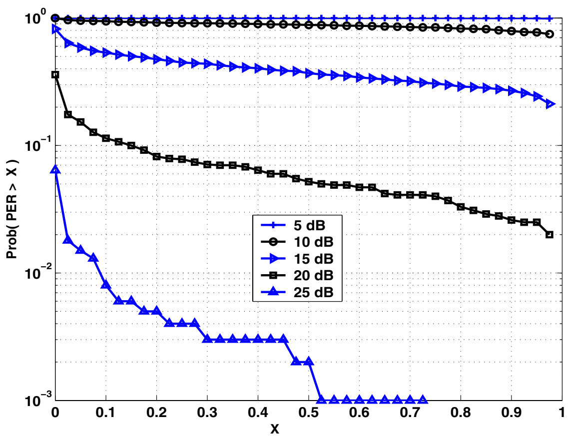

Fig. 3. **CCDF of PER for 24 Mbps at $\widetilde{SNR}$ = 5 - 25 dB**

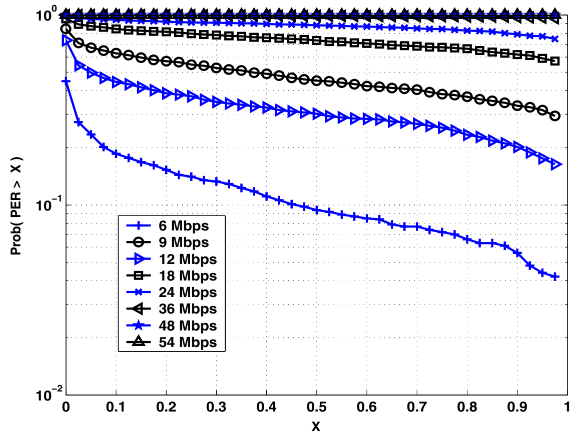

Fig. 4. **CCDF of PER for All data rates at $\widetilde{SNR}$ = 10 dB**

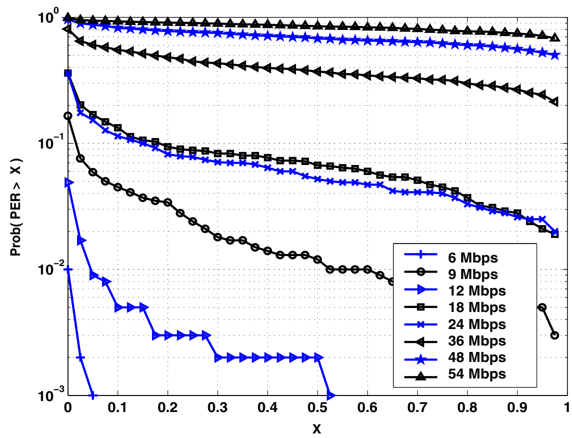

Fig. 5. **CCDF of PER for All data rates at $\widetilde{SNR}$ = 20 dB**

for $\widetilde{SNR}$ ranging from 5 to 25 dB. In Figs. 4, 5 and 6 we plot the CCDF for PER for all data rates for $\widetilde{SNR}$ = 10, 20 and 25 dB, respectively. In addition, we show in Tables II and III the average and the variance of PER for all data rates at various $\widetilde{SNR}$ values. As expected, for each data rate considered, the average PER and Pr$\{PER > X\}$ for any given X decrease as $\widetilde{SNR}$ increases. From the above results we can make the following observations: for any given data rate, there is a range of low $\widetilde{SNR}$ values such that PER is quite high and the PER variance is low; the system performance is very poor regardless of the fading realization. There is a range of high $\widetilde{SNR}$ values such that PER is quite low and the PER variance is low; the system performance is very good regardless of the fading realization. For mid-range $\widetilde{SNR}$ values, the performance is dependent on the particular fading realization experienced. In this case, the system performance may be quite good or poor.

To illustrate these observations, we consider the data rate of 24 Mbps and we note that for $\widetilde{SNR}$ = 5 dB, PER is in the range of 0.162 and 1 with an average PER of 0.999 and a variance of 8.00x10^{-4}. For $\widetilde{SNR}$ = 25 dB, PER is in the range of 0 and 0.748 with an average PER of 0.004 and a

TABLE II
AVERAGE PER

	$\widetilde{\text{SNR}}$ (dB)						
Data Rates (Mbps)	**5**	**10**	**15**	**20**	**25**	**30**	**35**
6	0.513	0.113	0.010	2.0x10^{-4}	1.0x10^{-6}	0.000	0.000
9	0.869	0.471	0.135	0.019	1.6x10^{-3}	0.000	0.000
12	0.811	0.316	0.048	0.002	1.1x10^{-5}	0.000	0.000
18	0.970	0.734	0.318	0.075	0.008	0.000	0.000
24	0.999	0.875	0.387	0.065	0.004	0.000	0.000
36	1.000	0.988	0.815	0.392	0.100	0.014	0.000
48	1.000	1.000	0.974	0.690	0.232	0.036	0.002
54	1.000	1.000	0.993	0.842	0.415	0.105	0.015

TABLE III
VARIANCE OF PER

	$\widetilde{\text{SNR}}$ (dB)						
Data Rates (Mbps)	**5**	**10**	**15**	**20**	**25**	**30**	**35**
6	1.9x10^{-1}	6.9x10^{-2}	5.3x10^{-3}	7.3x10^{-6}	1.0x10^{-9}	N/A	N/A
9	8.3x10^{-2}	1.9x10^{-1}	8.1x10^{-2}	1.0x10^{-2}	6.0x10^{-4}	N/A	N/A
12	1.1x10^{-1}	1.6x10^{-1}	3.1x10^{-2}	7.4x10^{-4}	5.5x10^{-8}	N/A	N/A
18	2.0x10^{-2}	1.5x10^{-1}	1.6x10^{-1}	4.6x10^{-2}	3.8x10^{-3}	N/A	N/A
24	8.0x10^{-4}	7.8x10^{-2}	1.8x10^{-1}	4.0x10^{-2}	1.3x10^{-3}	N/A	N/A
36	0.000	6.8x10^{-3}	1.1x10^{-1}	1.8x10^{-1}	6.1x10^{-2}	6.8x10^{-3}	N/A
48	0.000	0.000	1.6x10^{-2}	1.6x10^{-1}	1.3x10^{-1}	2.1x10^{-2}	2.4x10^{-4}
54	0.000	0.000	3.4x10^{-3}	9.1x10^{-2}	1.8x10^{-1}	6.2x10^{-2}	6.9x10^{-3}

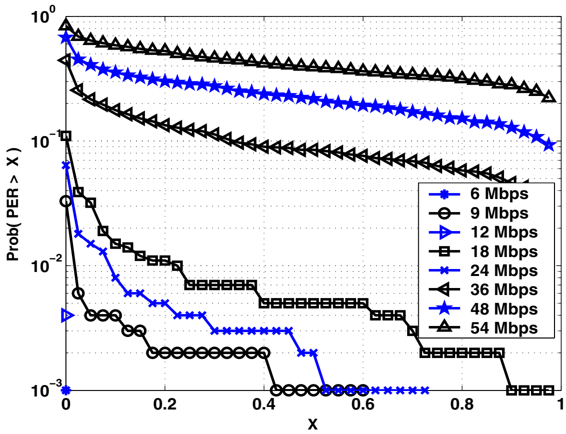

Fig. 6. **CCDF of PER for All data rates at $\widetilde{\text{SNR}}$ = 25 dB**

variance of 1.3x10^{-3}. For $\widetilde{SNR}$ = 15 dB, PER is in the range of 0 and 1 with an average PER of 0.387 and a variance of 0.18.

We note that the range of values of $\widetilde{SNR}$ referred to above depends on the data rate. We also note that for the same $\widetilde{SNR}$, the lower the data rate is, the better is the performance. This can be easily seen from Figs. 4, 5 and 6. Two anomalies to this statement are worth mentioning. The performance in PER for 9 Mbps is worse than that of 12 Mbps for all $\widetilde{SNR}$s considered. This anomaly is widely reported in the literature; see [6], [10]. The other anomaly is in the relative performance of the data rates of 18 and 24 Mbps. The PER performance of 18 Mbps is better than 24 Mbps at low $\widetilde{SNR}$ (Fig. 4) however at 20dB (Fig. 5), their respective performance is practically the same, while at 25 dB (Fig. 6), the performance of 24 Mbps is better than that of 18 Mbps. This anomaly can be also seen in the numerical results obtained in [8]. We can conclude that when $\widetilde{SNR}$ is sufficiently high to allow a high data rate modulation to operate satisfactorily, the degrading effect of the high code rate (i.e. $\frac{2}{3}$,$\frac{3}{4}$) in a lower data rate mode becomes dominant enough to cause the lower data rate mode to be outperformed by the higher data rate mode in which a low code rate (i.e. $\frac{1}{2}$) is employed.

IV. VOIP QUALITY ASSESSMENT

We consider the evaluation of VoIP quality by specifying a particular target value for MOS, MOS_t and a bound ε on the probability that the MOS_t is not achieved, that is, $\Pr\{MOS \leq MOS_t\} < \varepsilon$. To study voice quality, we present the results in Table IV where we give the probability that

TABLE IV

Pr $\{MOS \leq MOS_t\}$ for 6, 12, 24, 48 and 54 Mbps for $\widetilde{\text{SNR}}$=5-35dB

6 (Mbps)						
$\widetilde{\text{SNR}}$ (dB)	**Dist. (Meters)**	**MOS$_t$ = 2.6**	**MOS$_t$ = 3.6**	**MOS$_t$ = 4**	**MOS$_t$ = 4.3**	**Ave. MOS**
5	52	0.625	0.669	0.686	0.722	2.26
10	44	0.140	0.169	0.185	0.232	3.96
15	36	0.015	0.020	0.021	0.032	4.43
20	28	0.000	0.000	0.000	0.001	4.50
25	23	0.000	0.000	0.000	0.000	4.50
12 (Mbps)						
$\widetilde{\text{SNR}}$ (dB)	**Dist. (Meters)**	**MOS$_t$ = 2.6**	**MOS$_t$ = 3.6**	**MOS$_t$ = 4**	**MOS$_t$ = 4.3**	**Ave. MOS**
5	52	0.872	0.893	0.907	0.918	1.43
10	44	0.374	0.419	0.445	0.493	3.14
15	36	0.063	0.072	0.082	0.113	4.27
20	28	0.003	0.005	0.005	0.009	4.49
25	23	0.000	0.000	0.000	0.000	4.50
24 (Mbps)						
$\widetilde{\text{SNR}}$ (dB)	**Dist. (Meters)**	**MOS$_t$ = 2.6**	**MOS$_t$ = 3.6**	**MOS$_t$ = 4**	**MOS$_t$ = 4.3**	**Ave. MOS**
5	52	0.999	1.000	1.000	1.000	1.00
10	44	0.913	0.932	0.944	0.953	1.28
15	36	0.451	0.504	0.537	0.583	2.85
20	28	0.079	0.101	0.114	0.148	4.19
25	23	0.004	0.006	0.008	0.015	4.48
48 (Mbps)						
$\widetilde{\text{SNR}}$ (dB)	**Dist. (Meters)**	**MOS$_t$ = 2.6**	**MOS$_t$ = 3.6**	**MOS$_t$ = 4**	**MOS$_t$ = 4.3**	**Ave. MOS**
15	36	0.985	0.993	0.996	0.998	1.04
20	28	0.765	0.802	0.824	0.872	1.78
25	23	0.289	0.327	0.358	0.403	3.43
30	17	0.048	0.060	0.068	0.077	4.32
35	12	0.001	0.004	0.004	0.009	4.49
54 (Mbps)						
$\widetilde{\text{SNR}}$ (dB)	**Dist. (Meters)**	**MOS$_t$ = 2.6**	**MOS$_t$ = 3.6**	**MOS$_t$ = 4**	**MOS$_t$ = 4.3**	**Ave. MOS**
15	36	0.999	0.999	0.999	0.999	1.01
20	28	0.903	0.918	0.928	0.941	1.34
25	23	0.490	0.555	0.589	0.639	2.71
30	17	0.128	0.168	0.190	0.231	3.99
35	12	0.020	0.024	0.033	0.046	4.42

MOS is below MOS_t, for MOS_t = 2.6, 3.6, 4 and 4.3 for data rates 6, 12, 24, 48 and 54 Mbps and various values of $\widetilde{SNR}$ (translated to distances). We also show the average MOS obtained by averaging over all fading realizations considered in the simulation. These results correspond to a single transmission for VoIP packets (i.e. no retransmissions).

Clearly, as we have seen already in the numerical results for PER, for a given data rate, increasing $\widetilde{SNR}$ (i.e. decreasing the distance between the communicating VoIP devices) or decreasing the data rate for a given $\widetilde{SNR}$ (a given distance) leads to an improvement in performance.

From Table IV, it is easy to identify the combinations of data rates and $\widetilde{SNR}$ (distance) that can meet a requirement in terms MOS_t and ε. An interesting observation is that for given data rate and distance, while Pr$\{MOS \leq 2.6\} \leq$ Pr$\{MOS \leq 3.6\}$ $\leq$ Pr$\{MOS \leq 4\}$ the difference between these probabilities is relatively small. For example, for 24 Mbps and $\widetilde{SNR}$ = 20 dB (distance = 28 m), we have $Pr\{MOS \leq 2.6 | MOS \leq 4.0\} = \frac{0.08}{0.11} = 0.72$. This means that the specific choice of MOS_t is not so critical and that a large fraction of calls that do not meet MOS_t are actually in the range of MOS that is not recommended (MOS < 2.6). This prompts one to choose a value of ε that is small (on the order of 0.01).

Consider now MOS_t = 4.0 and ε = 0.01. To meet such a requirement, for each data rate there is a distance that may not be exceeded. For example, the maximum possible distance for 6, 12, 24, 48 and 54 Mbps is 32, 29, 23, 13 and 11 meters, respectively. (These distances are obtained by linear interpolation of the data presented in Table IV).

From Table IV, it is possible to see how inaccurate the average MOS is in reflecting the true VoIP performance. Take for example the case of 24 Mbps and $\widetilde{SNR}$ = 20 dB (distance 28 m); while the average MOS is 4.19, we find an 11% chance of MOS falling below 4.0, 10% chance of falling below 3.6 and 8% chance of falling below 2.6. From the table, we see that the performance is acceptable when the distance is reduced to 23 m for which the average MOS is 4.48.

So far in this section, we considered the evaluation of VoIP assuming that a packet is transmitted only once. The question arises as to what improvement would be obtained if a VoIP packet could be retransmitted when it is in error. We show the results corresponding to a maximum of 3 transmissions per packet in Table V. It is quite clear from the table that for a given data rate and distance, the probability that MOS is below a target is reduced; however the improvement in distance is data rate dependent and is less significant for higher data rates than for lower data rates. For example, while it is possible to gain 4 meters in distance at 6 Mbps, at 24 Mbps, the improvement is less than one meter (for the same ε = 0.01 considered above).

All the results presented up to this point were obtained under the assumption of perfect channel estimates at the receiver. However in practice, there are channel estimation errors due to noise in the channel. To investigate the impact of channel estimation errors on VoIP performance, we applied the TDLS channel estimator to the two training sequences in the preamble at the receiver in order to acquire the channel. In Table VI, we present the Pr$\{MOS \leq MOS_t\}$ for $MOS_t =$ 2.6, 3.6, 4 and 4.3 for data rates 24 and 54 Mbps at $\widetilde{SNR}$ values of interest. By comparing the results in Table VI with the corresponding results in Table IV, we conclude that the differences are minimal. These results suggests that the two training sequences specified in the standards are adequate for near-to-perfect channel estimation in a time-invariant channel.

Finally, we emphasize the importance of fading in performance evaluation of WLANs in general and VoIP over WLANs in particular by comparing the average MOS in Table IV (last column in the table) to that obtained by ignoring fading altogether shown in Table VII.

V. Conclusion

We showed the impact of fading in wireless channels on the performance of VoIP in IEEE 802.11a systems and

TABLE V

Pr $\{MOS \leq MOS_t\}$ WITH 3 RETRANSMISSIONS FOR 6, 12, 24, 48 AND 54 MBPS FOR $\widetilde{\text{SNR}}$ = 5 - 35 dB

6 (Mbps)						
$\widetilde{\text{SNR}}$ (dB)	Dist. (Meters)	MOS$_t$ = 2.6	MOS$_t$ = 3.6	MOS$_t$ = 4	MOS$_t$ = 4.3	Ave. MOS
5	52	0.460	0.499	0.515	0.541	2.82
10	44	0.084	0.092	0.100	0.118	4.19
15	36	0.006	0.007	0.007	0.010	4.48
20	28	0.000	0.000	0.000	0.000	4.50
25	23	0.000	0.000	0.000	0.000	4.50
12 (Mbps)						
$\widetilde{\text{SNR}}$ (dB)	Dist. (Meters)	MOS$_t$ = 2.6	MOS$_t$ = 3.6	MOS$_t$ = 4	MOS$_t$ = 4.3	Ave. MOS
5	52	0.784	0.808	0.820	0.845	1.73
10	44	0.282	0.291	0.310	0.330	3.50
15	36	0.033	0.041	0.044	0.047	4.37
20	28	0.000	0.001	0.002	0.002	4.50
25	23	0.000	0.000	0.000	0.000	4.50
24 (Mbps)						
$\widetilde{\text{SNR}}$ (dB)	Dist. (Meters)	MOS$_t$ = 2.6	MOS$_t$ = 3.6	MOS$_t$ = 4	MOS$_t$ = 4.3	Ave. MOS
5	52	0.999	0.999	0.999	0.999	1.00
10	44	0.864	0.879	0.889	0.902	1.46
15	36	0.337	0.361	0.386	0.409	3.29
20	28	0.047	0.050	0.055	0.068	4.33
25	23	0.001	0.001	0.002	0.003	4.50
48 (Mbps)						
$\widetilde{\text{SNR}}$ (dB)	Dist. (Meters)	MOS$_t$ = 2.6	MOS$_t$ = 3.6	MOS$_t$ = 4	MOS$_t$ = 4.3	Ave. MOS
15	36	0.973	0.976	0.977	0.980	1.10
20	28	0.650	0.674	0.695	0.718	2.19
25	23	0.190	0.207	0.227	0.248	3.81
30	17	0.023	0.025	0.029	0.032	4.42
35	12	0.000	0.000	0.000	0.000	4.50
54 (Mbps)						
$\widetilde{\text{SNR}}$ (dB)	Dist. (Meters)	MOS$_t$ = 2.6	MOS$_t$ = 3.6	MOS$_t$ = 4	MOS$_t$ = 4.3	Ave. MOS
15	36	0.993	0.996	0.996	0.998	1.02
20	28	0.829	0.844	0.858	0.876	1.59
25	23	0.358	0.386	0.401	0.434	3.21
30	17	0.075	0.081	0.090	0.102	4.23
35	12	0.005	0.010	0.012	0.014	4.47

how overly optimistic the assessment of VoIP performance could be if fading is ignored. We derived the distributions of VoIP performance for all data rates specified in the IEEE 802.11a standard and for a range of typical signal-to-noise ratio scenarios. We assessed VoIP performance in terms of Pr$\{MOS \leq MOS_t\} < \varepsilon$ where MOS_t represents a desirable level of user-satisfaction and ε, a bound on the probability of not achieving this target. From our results, we observe that the value of ε has a strong influence (stronger than MOS_t) on the system parameters (distance and data rate) that achieves the desirable results.

TABLE VI

Pr $\{MOS \leq MOS_t\}$ FOR 24 AND 54 MBPS FOR $\widetilde{\text{SNR}}$ = 20 - 35 dB WITH CHANNEL ESTIMATION ERRORS

$\widetilde{\text{SNR}}$ (dB)	Dist. (Meters)	MOS$_t$ = 2.6	MOS$_t$ = 3.6	MOS$_t$ = 4	MOS$_t$ = 4.3	Ave. MOS
24 (Mbps)						
20	28	0.089	0.112	0.131	0.165	4.15
25	23	0.005	0.008	0.011	0.017	4.48
54 (Mbps)						
30	17	0.145	0.184	0.209	0.250	3.94
35	12	0.023	0.030	0.038	0.055	4.41

TABLE VII

AVERAGE MOS IN A NON-FADING CHANNEL

	Data Rates (Mbps)							
$\widetilde{\text{SNR}}$ (dB)	6	9	12	18	24	36	48	54
5	4.50	4.43	3.84	1.00	1.00	1.00	1.00	1.00
10	4.50	4.50	4.50	4.50	1.00	1.00	1.00	1.00
15	4.50	4.50	4.50	4.50	4.50	4.49	1.00	1.00
20	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.08
25	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50

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