Performance Loss Due to Multipath Propagation for IEEE 802.11 Systems

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***Abstract*—In this work, we developed an analytical estimation of the performance loss due to multipath propagation for a narrowband OFDM system. The propagation characteristics required for this loss estimation, are experimentally determined by virtual SIMO measurements in a large conference room where repeated reception problems were reported for an IEEE 802.11 system, as well as in 2 other large conference rooms for comparison. The resulting losses due to multipath are calculated for IEEE 802.11a/n and related to the propagation characteristics.**

***Index Terms*—multipath, loss, reverberation time, IEEE 802.11**

I. INTRODUCTION

The performance degradation of OFDM (orthogonal frequency-division multiplexing) systems due to propagation delay is frequently estimated by comparing the cyclic prefix length and the delay spread. However, in this way, the degradation is not specified quantitatively. In literature, many theoretical studies are available on the SNR (signal-to-noise ratio) degradation (or loss) due to system impairments (such as timing and frequency offset) [1], but almost no studies which focus on the multipath channel can be found. Moreover, this work is focused on large conference rooms, which is a rarely studied environment. A path loss model for large conference rooms for IEEE 802.11n has been developed in our previous work [2].

In this work, the loss due to multipath propagation is estimated for a large conference room where repeated reception problems were reported for an IEEE 802.11 system. This estimation is based on an analytical expression as a function of the reverberation parameters of the channel (Section II). Our work is focused on narrowband OFDM systems (e.g. IEEE 802.11a/n [3]), which are designed in the assumption that there is no signal distortion over the FFT (fast Fourier transform) window due to a relatively high cyclic prefix and FFT period. The required propagation characteristics are experimentally determined by virtual SIMO (Single-Input Multiple-Output) measurements in this room, as well as in 2 other large conference rooms for comparison (Section III). Finally, the resulting losses due to multipath are calculated for IEEE 802.11a/n and related to the propagation characteristics (Section IV).

II. ANALYTICAL ESTIMATION OF THE LOSS DUE TO MULIPATH PROPAGATION

A. Determination of the symbol error vector due to multipath

We determined the symbol error vector for an *idealized* narrowband OFDM system. Here, only 2 impairments are considered: additive white Gaussian noise (AWGN) and a multipath channel (causing a distorted OFDM signal over the FFT window when the propagation delay exceeds the cyclic prefix). Thus, we assume (i) an optimal FFT window positioning (no symbol timing offset), (ii) no frequency offset, phase noise, I/Q imbalance, (iii) no synchronization algorithms, (iv) a one-tap FEQ (frequency domain equalizer) equalization scheme (without intersymbol/intercarrier cancellation), (v) an infinite sample rate and (vi) no Doppler effect and a static channel during one OFDM block. For the time-domain windowing (at the transmitter), we assume a rectangular pulse.

This *idealized* OFDM system can be analytically modeled as follows [4] [5]. The transmitted OFDM signal v_T is obtained by modulating the (complex-valued) (normalized) data symbols $\tilde{X}_i$ (for $-N \leq i \leq N$) on the $2N+1$ subcarriers, using a rectangular pulse with a duration of $P+CP$, where P is the FFT period and CP is the cyclic prefix length. The signal at the receiver input (v_R) is determined based on the impulse response $c(\tau)$ of the system with v_T as input and v_R as output. A typical receiver architecture [5] is considered to determine the I/Q components at the output of the analog receiver circuit. A Fourier transform (decomposition into a Fourier series) is applied on the signal over the FFT window. Finally, the resulting FFT output for each subcarrier is divided by the corresponding channel response (one-tap FEQ) to obtain the data symbols $\tilde{Y}_{i'}$ (for $-N \leq i' \leq N$) as detected by the demodulator. The symbol error vector (i.e. $\tilde{Y}_{i'} - \tilde{X}_{i'}$) is composed of a contribution due to multipath ($\Delta\tilde{Y}_{i',delay}$) and a contribution due to AWGN noise ($\Delta\tilde{Y}_{i',AWGN}$).

The symbol error vector $\Delta\tilde{Y}_{i',delay}$ is calculated analytically using a method which is based on [4]. Here, the decomposition into a Fourier series is related to the continuous Fourier transform of the received signal multiplied by a rectangular pulse over the FFT window. Based on our results, we can assume that an optimal FFT window positioning is obtained when the FFT window starts CP later than the start of the received OFDM signal. Finally, the symbol error vector due to multipath can be determined analytically based on the channel impulse response and is a sum of terms proportional to the data symbols of the current and the preceding OFDM symbol, referred to as $\tilde{X}_i$ and $\tilde{X}'_i$, respectively. The terms proportional to $\tilde{X}'_i$ (for $-N \leq i \leq N$) are due to intersymbol interference (ISI), while the terms proportional to $\tilde{X}_i$ (for $-N \leq i \leq N$ and $i \neq i'$) are due to intercarrier interference (ICI). The term proportional to $\tilde{X}_{i'}$ is due to a channel estimation error. The terms proportional to $\tilde{X}_i$ and $\tilde{X}_i'$, resp. have the same power. Using the analytical expression based on $c(\tau)$, the symbol error $\Delta\tilde{Y}_{i',delay}$ can be calculated in good approximation based on the measured channel response (with a finite frequency range and a finite frequency resolution).

B. Performance loss due to multipath

We assume that for a realistic OFDM system, the error on the equalized symbol (detected by the demodulator) can be decomposed as follows:

$$\tilde{Y}_i = \tilde{X}_i + \Delta\tilde{Y}_{i,AWGN\,channel} + \Delta\tilde{Y}_{i,real\,channel} \ , \quad (1)$$

where $\Delta\tilde{Y}_{i,AWGN\,channel}$ is the error caused by all system impairments in the case of an AWGN channel and $\Delta\tilde{Y}_{i,real\,channel}$ is the error caused by all impairments related to the realistic channel (deviating from an AWGN channel). Thus, the former error is mainly due to a clock or carrier frequency offset, a symbol timing offset, phase noise, I/Q imbalance or AWGN noise, while the latter error is mainly due to a Doppler shift, a non-static channel or multipath propagation (causing a symbol timing offset (due to signal distortion) or signal distortion over the FFT window).

The error $\Delta\tilde{Y}_{i,AWGN\,channel}$ corresponds to the error in the case of a realistic system with an AWGN channel (i.e., when transmitter and receiver are connected by a cable). Concerning $\Delta\tilde{Y}_{i,real\,channel}$, we only consider errors due to signal distortion over the FFT window and consider no additional errors due to the realistic synchronization algorithms. This situation corresponds to the *idealized* OFDM system: $\Delta\tilde{Y}_{i,real\,channel} = \Delta\tilde{Y}_{i,delay}$ (see Section II-A). Thus, the loss due to propagation delay which will be determined based on $\Delta\tilde{Y}_{i,delay}$ can be considered as a lower limit for realistic OFDM systems.

We define the *instantaneous* signal-to-noise ratio SNR_{inst} as the ratio between (i) the (errorless) signal power, averaged over all constellation points ($(|\tilde{X}_i|^2)_{av}$), and (ii) the average power of the symbol error vector $\Delta\tilde{Y}_{i,therm}$ due to the thermal noise entering the receiver input:

$$SNR_{inst} = \frac{(|\tilde{X}_i|^2)_{av}}{\langle|\Delta\tilde{Y}_{i,therm}|^2\rangle}. \quad (2)$$

SNR_{inst} is called *instantaneous* because it is based on one channel realization.

To obtain a certain PER (packet error rate), a certain minimum (instantaneous) SNR SNR_{inst} is required to ensure that the signal strength is large enough compared to the symbol error vectors due to AWGN noise and other imperfections. In the case of only thermal noise entering the receiver input (i.e., with an average power per subcarrier being k_BT/P, where k_B is the Boltzmann constant and T is the temperature), the minimum required *instantaneous* signal-to-noise ratio $SNR_{inst,therm}$ is lower than for a realistic system with AWGN channel ($SNR_{inst,AWGNchannel}$):

$$SNR_{inst,AWGNchannel} = SNR_{inst,therm} F_{lin} IL_{lin}, \quad (3)$$

where F_{lin} is the noise factor (being the noise figure F in linear scale) and IL_{lin} is the implementation loss (IL (dB)) in linear scale. Analogously, the minimum required SNR $SNR_{inst,delay}$ in the case of only symbol error $\Delta\tilde{Y}_{i,delay}$ is expressed as $SNR_{inst,therm}$ multiplied by a factor $L_{block,lin}$:

$$SNR_{inst,delay} = SNR_{inst,therm} L_{block,lin}. \quad (4)$$

If L_{block} (being $L_{block,lin}$ in dB scale) is much larger (in linear terms) than $F+IL$, the symbol error $\Delta\tilde{Y}_{i,AWGN\,channel}$ is negligible compared to $\Delta\tilde{Y}_{i,real\,channel}$ with respect to the minimum required total $SNR_{inst,tot}$ (considered per OFDM block), which is then $SNR_{inst,therm} + L_{block}$ (dB). If L_{block} is much smaller than $F+IL$, the symbol error $\Delta\tilde{Y}_{i,real\,channel}$ is negligible compared to $\Delta\tilde{Y}_{i,AWGN\,channel}$ with respect to the minimum required total $SNR_{inst,tot}$, which is then $SNR_{inst,therm} + F + IL$ (dB). Consequently, the minimum required total $SNR_{inst,tot}$ could be expressed as (in linear scale)

$$SNR_{inst,tot} = SNR_{inst,therm}(F_{lin} IL_{lin} + L_{block,lin}). \quad (5)$$

Assuming that $\Delta\tilde{Y}_{i,delay}$ can be considered as a complex Gaussian variable, $SNR_{inst,delay}$ can be determined based on the ratio between the average power of $\Delta\tilde{Y}_{delay}$ and $\Delta\tilde{Y}_{therm}$:

$$L_{block,lin} = \langle|\Delta\tilde{Y}_{delay}|^2\rangle / \langle|\Delta\tilde{Y}_{therm}|^2\rangle. \quad (6)$$

Here, the average is based on one channel realization. As the channel can vary over different OFDM blocks, $L_{block,lin}$ and $SNR_{inst,delay}$ are block-dependent. However, it can be shown that when taking the average in (6) over all channel realizations, an effective value is obtained with respect to the outage probability (i.e. the probability that the required PER is not achieved for one OFDM block (due to fading) [6]).

The new proposed $SNR_{inst,tot}$ corresponds to a new receiver sensitivity $P_{sens,tot}$ (mW) :

$$P_{sens,tot} = P_{sens,AWGNchannel}\left(1 + \frac{L_{block,lin}}{F_{lin} IL_{lin}}\right), \quad (7)$$

where $P_{sens,AWGNchannel}$ is the conventional receiver sensitivity (mW) (i.e. for a realistic system with an AWGN channel). The reception quality is completely comparable to the situation where the transmit power of the realistic system is reduced by a certain factor and the multipath aspect of the channel is not considered, as can be seen when using (7) in link budget analysis. This transmit power reduction or loss L_{delay} is then (in linear terms)

$$L_{delay} = 1 + \frac{L_{block,lin}}{F_{lin} IL_{lin}}. \quad (8)$$

An analytical estimation of the average power of $\Delta\tilde{Y}_{i',delay}$ can be determined as follows. First, based on Section II-A, the average power of $\Delta\tilde{Y}_{i',delay}$ can be expressed based on the averaged power delay profile (APDP). Secondly, for narrowband OFDM systems, $\Delta\tilde{Y}_{i',delay}$ is based on the diffuse part of the channel, where according to the theory of room electromagnetics [7] [8] the APDP can be described as follows:

$$C_k = P_0 \exp\big(-(\tau - \tau_{min})/\tau_r\big), \tag{9}$$

where C_k are the power coefficients of the APDP, τ_r is the reverberation time and τ_{min} is the minimum delay occurring in the APDP. In this way, the average power of $\Delta\tilde{Y}_{i',delay}$ can be determined analytically as a function of P, CP and τ_r and I_0, defined as $I_0 = P_0\Delta f_0$, where Δf_0 is the width of the Hann window applied to the measured channel response.

III. MEASUREMENTS

Measurements were executed with a virtual SIMO system in three conference rooms. In this setup, the Tx and Rx antenna, both broadband omnidirectional Electro-Metrics antennas of type EM-6116, were connected to a Rohde & Schwarz ZVR vector network analyzer, which measured the scattering parameter S_{21} as a function of the frequency. A coaxial cable with two amplifiers was used to realize the required Tx-Rx separation. The position of the Rx antenna, attached to a frame of BiSlides, was controlled by a laptop to realize a virtual array.

In the first room (room A), repeated reception problems were reported with an IEEE 802.11 conference system. This conference system has a SISO (Single-Input Single-Output) configuration without antenna diversity. According to the manufacturer, these problems only occur in this conference room and cannot be attributed to interference sources after spectral analysis. One wall of room A contains about 30 metal HVAC (Heating, Ventilation, and Air Conditioning) plates (dimension 1 m by 1.5 m). The ceiling, which looks like a part of an ellipsoid, contains a metal wire mesh, with a minimal separation of about 1 cm. The dimensions of the room are 12 m × 53 m and the ceiling has a maximal height of 13 m. For comparison, measurements were also executed in 2 other large conference rooms (room B and C). The dimensions of room B are 10 m × 32 m and the ceiling, which is approximately a horizontal plane, has a height of about 6 m. Room C is cylinder-shaped with about 30 m diameter and a height of about 7 m. For all measurements (rooms A, B and C), there was a line-of-sight condition.

The measurements were done in the frequency range 2.5 – 3 GHz. In room A and B, 801 frequency points were used, which allows to resolve power delay profiles for delays up to 1.6 µs (greater than the 802.11n Guard Interval of 800 ns [9]). This delay corresponds to a path length of about 475 m. A 23×23 Rx array was used, with a separation of 1.5 cm. This corresponds to 3.6 samples per $\lambda/2$ (where λ is the wavelength), and a total array dimension of 3λ. In room C, the following settings were used: 401 frequency points, a 4×4 Rx array with a separation of 4 cm.

IV. ESTIMATION OF THE LOSS DUE TO MULTIPATH FOR SPECIFIC ROOMS

In this section, the proposed expression for the loss due to multipath is applied to rooms A, B and C. We consider a CP length of $400/800$ ns (which are the CP values specified for IEEE 802.11a/n) and an FFT period of 3.2 µs (as specified for 802.11a/n). The channel parameters τ_r and P_0 are determined from the APDPs, obtained by averaging the power delay profiles for all Rx positions (of the array). For all rooms, a Hann window width Δf_0 of 300 MHz is chosen. Finally, the determined parameters τ_r and $P_0\Delta f_0$ (indicating the intensity of the diffuse component) are determined from the APDPs according to (9) (Table I). Compared to rooms B and C, the intensity of the diffuse multipath component (DMC) in room A is much higher at a delay of 400 ns and a fortiori at a delay of 800 ns, due to the higher reverberation time in room A (Table I). For each room, L_{delay} is calculated using (8) and (6). With the focus on a lower limit for the loss, we consider rather high values for the noise figure F and the implementation loss IL: $F = 10$ dB and $IL = 5$ dB (as proposed for 802.11a in [10]). A bandwidth of 20 MHz (as specified for 802.11a) is considered.

	$\tau_r(ns)$	I_0 (Hz)	CP (ns)	L_{delay} (dB) (for $P_T = 20/30$ dBm)
room A	131	2.6	400	19.3 / 29.2
			800	7.0 / 16.1
room B	36	9.0	400	0.0 / 0.3
			800	0.0 / 0.0
room C	56	9.0	400	2.8 / 10.1
			800	0.0 / 0.0

Table I

THE REVERBERATION TIME (τ_r) AND THE INTENSITY OF THE DIFFUSE COMPONENT (I_0) ARE DETERMINED FOR DIFFERENT ROOMS, WHERE VIRTUAL SIMO MEASUREMENTS WERE EXECUTED. BASED ON THESE PROPAGATION CHARACTERISTICS, THE (PREDICTED) LOSS L_{delay} DUE TO MULTIPATH IS CALCULATED FOR TRANSMIT POWER $P_T = 20 - 30$ dBm.

The loss L_{delay} for a transmit power of 20 dBm and 30 dBm resp. is given for each room in Table I. In room B, the predicted loss due to multipath is completely negligible. In room C, the loss is negligible for $CP = 800$ ns, but not for $CP = 400$ ns (up to 10 dB for $P_T = 30$ dBm). In room A, the loss cannot be neglected even for $P_T = 20$ dBm and $CP = 800$ ns ($L_{delay} = 7$ dB) and can become severe (up to $L_{delay} = 29$ dB for $P_T = 30$ dBm and $CP = 400$ ns). Note that our proposed estimation of the loss due to multipath is to be considered as a lower limit for realistic systems.

Although the intensity of the diffuse component (I_0) for room A is lower than for room B and C (Table I), the loss due to multipath is higher, because the reverberation time, which is strikingly higher for room A, is the dominant factor. This can be seen in Fig. 1, which shows the APDP in room A. According to our estimation of the multipath loss, $L_{block,lin}$ is approximately proportional to

$$L_{block,lin} \propto \frac{P_T}{BW} I_0 \frac{\tau_r^2}{P} \exp(-CP/\tau_r). \tag{10}$$

From (10), it can also be seen that the multipath loss decreases with decreasing reverberation time, with increasing cyclic prefix duration, with increasing FFT period and with decreasing transmit power.

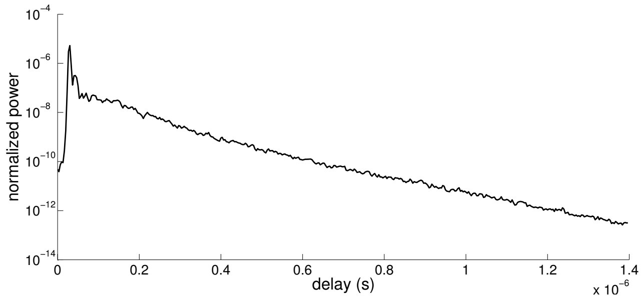

Figure 1. The APDP based on virtual SIMO measurements in room A. A high reverberation time of 131 ns is found.

V. CONCLUSION

In this work, we developed an analytical estimation of the performance loss due to multipath propagation for a narrowband OFDM system. The propagation characteristics required for this loss due to multipath estimation, are experimentally determined by virtual SIMO measurements in a large conference room (room A) where repeated reception problems were reported for an IEEE 802.11 system, as well as in 2 other large conference rooms for comparison (rooms B and C). The resulting losses due to multipath, calculated for IEEE 802.11a/n, are much higher in room A than in rooms B and C: e.g. for a 800 ns cyclic prefix and a 30 dBm transmit power, the predicted loss is 16 dB in room A, while no loss is predicted for rooms B and C. The severe performance degradation in room A can be attributed to a relatively high reverberation time.

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