Analysis of 802.11 OFDM in High Multipath Environments

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**Abstract**—The performance loss of 802.11 OFDM systems due to propagation delay spread has been analyzed as a function of OFDM parameters for a wide range of reverberation times. This analysis results into solutions for the OFDM design to suppress the performance degradation.

**Index Terms**—delay spread; diffuse multipath; reverberation time; OFDM; room electromagnetics

I. INTRODUCTION

The performance of OFDM (orthogonal frequency-division multiplexing) systems can be degraded by the signal distortion over the FFT (fast Fourier transform) window caused by the propagation delay spread. In [1], we proposed to describe this effect in narrowband OFDM systems (such as IEEE 802.11a/g/n/ac) by an additive white Gaussian noise (AWGN) noise, characterized by a noise factor \(F_{\text{delay}}\). This effect originates from replicas of the transmitted OFDM pulse with a delay larger than the cyclic prefix length \(CP\). The intensity of these propagation paths can be high, especially in indoor environments, resulting into intersymbol and intercarrier (ISI/ICI) interference. For delays larger than \(CP\), the channel typically consists of diffuse multipath components only. Here, the theory of room electromagnetics is applicable [2], according to which the averaged power delay profile (APDP) decays exponentially. This APDP decay is characterized by the time constant \(\tau_{s}\), referred to as the reverberation time, and the intensity parameter \(I_{\text{diff}}\) [Hz] [1]. As \(P_{0}\), the APDP power coefficient of first arriving path, is dependent on the frequency width \(\Delta f_{0}\) of the Hann window applied to obtain the APDP, the intensity of the diffuse field will be expressed by the physical parameter \(I_{\text{diff}}\), defined by \(I_{\text{diff}} = P_{0}\Delta f_{0}\) [1]. Based on this theory, an analytical expression of \(F_{\text{delay}}\) has been developed in [1] in terms of OFDM parameters and the propagation parameters \(\tau_{s}\) and \(I_{\text{diff}}\).

In this work, a parametric analysis of \(F_{\text{delay}}\) is carried out as a function of OFDM parameters, based on the aforementioned analytical expression for \(F_{\text{delay}}\). This analysis is done for typical IEEE 802.11a/g/n/ac parameters [3] [4]. This gives insight and solutions for the OFDM design to suppress the performance loss due to the propagation delay spread.

II. DETERMINATION OF \(F_{\text{delay}}\)

In [1], the performance loss due to the signal distortion over the FFT window (caused by the propagation delay spread), described by a loss factor \(L_{\text{delay}}\), has been related to the noise factor \(F_{\text{delay}}\) as follows:

\[
L_{\text{delay}} = 1 + \frac{F_{\text{delay}}}{F_{\text{lin}}IL_{\text{lin}}},
\]

where \(F_{\text{lin}}\) and \(IL_{\text{lin}}\) are the conventional (linear-scaled) noise factor and implementation loss of the receiver, resp. (i.e., corresponding to the situation where receiver and transmitter are connected by a cable). Therefore, our analysis will be done in terms of \(F_{\text{delay}}\).

For the purpose of this work, we rewrite the expression for \(F_{\text{delay}}\) from [1] as a function of the following relevant OFDM design parameters: the transmit power per frequency unit \(P_{\tau, f}\), the total bandwidth \(BW\) of the channel, the FFT period \(P\), \(CP\) and the sampling factor \(f_s\). The number of samples per FFT period \(N_{\text{sample}}\) is typically higher or equal than the total number of subcarriers, being \(BW \times N\). \(N_{\text{sample}}\) is usually expressed by means of the sampling factor \(f_s\):

\[
N_{\text{sample}} = f_s BW, \quad P, \quad N_{\text{sample}}\text{ is usually expressed by means of the sampling factor } f_s.
\]

III. PARAMETRIC ANALYSIS

In this section, the analytical estimation for \(F_{\text{delay}}\) is analyzed as a function of \(P\), \(CP\), \(BW\) and \(f_s\). All calculations of \(F_{\text{delay}}\) presented in this work are, unless otherwise mentioned, based on the 802.11a physical standard: \(P = 3.2\) μs, \(CP = 800\) ns, \(BW = 20\) MHz and \(f_s = 1\). We assume a typical value for \(I_{\text{diff}}\) of 6 Hz and a wide range of \(\tau_s\) varying from 10 ns to 200 ns, based on experimental results [1]. For our calculations, we assume \(P_{\tau, f} = 6.2 \times 10^{-9}\)W/Hz, based on a 20 dBm transmit power. For a 30 dBm transmit power, \(F_{\text{delay}}\) can be simply found as 10 dB higher, as \(F_{\text{delay}}\) is proportional to the transmit power [1].

A. Influence of the cyclic prefix duration \(CP\)

In Fig. 1, \(F_{\text{delay}}\) is shown as a function of \(CP\) for different \(\tau_s\). \(F_{\text{delay}}\) decreases strongly with increasing \(CP\), due to the fact that \(F_{\text{delay}}\) is proportional to \(\exp(-CP/\tau_s)\). Although the dependency of \(F_{\text{delay}}\) on \(CP\) is less strong for higher \(\tau_s\), increasing \(CP\) still provides an efficient strategy to reduce the interference due to delay spread. E.g., for \(\tau_s = 140\) ns, \(F_{\text{delay}}\) decreases from 28.6 dB to 3.8 dB when switching from an 800 ns \(CP\) to 1600 ns. This corresponds to a loss \(L_{\text{delay}}\) reduction of about 14 dB (see (1)). For a 30 dBm transmit power, the decrease of \(F_{\text{delay}}\) is even from 38.6 dB to 13.8 dB. When switching from an 800 ns \(CP\) to 1600 ns, the...
data rate is reduced with about 17%. However, this is largely compensated by the strong reduction of $L_{\text{delay}}$.

\[
\begin{array}{c|c}
\text{CP [ns]} & F_{\text{delay}} [\text{dB}] \\
\hline
0 & -1.0 \\
500 & 2.0 \\
1000 & 4.0 \\
1500 & 6.0 \\
2000 & 8.0 \\
2500 & 10.0 \\
3000 & 12.0 \\
3500 & 16.0 \\
\hline
\end{array}
\]

Figure 1. Calculated noise factor $F_{\text{delay}}$ as a function of cyclic prefix CP for different reverberation time $\tau_r$. This is based on IEEE 802.11a and a 20 dBm transmit power.

B. Influence of the FFT period $P$

We found that $F_{\text{delay}}$ is inversely proportionally to $P$. In our analysis, the effect on the theoretical (transmission) data rate $R_{\text{data}}$ (proportional to $P/(P + CP)$) and the hardware complexity (related to the number of used subcarriers, proportional to $BW \times P$) is taken into account simultaneously. A higher FFT period $P$ would result in a lower performance loss due to delay spread ($F_{\text{delay}}$) as well as higher data rate, but the FFT processor would also require a higher size. When switching from $P = 3.2$ $\mu$s to e.g., 6.4 $\mu$s, $F_{\text{delay}}$ would decrease with 3 dB and the data rate would increase with 11%. However, the FFT size would increase from 64 to 128. Therefore, increasing $P$ is not really an efficient strategy to suppress the performance loss due to delay spread.

C. Influence of the bandwidth $BW$

Increasing the bandwidth results into an increased $F_{\text{delay}}$ due to a reduced sampling period, which acts as an extension of the cyclic prefix. The dependency of $F_{\text{delay}}$ on $BW$ is rather slight. Comparing $BW = 160$ MHz (802.11ac) to 20 MHz, the increase of $F_{\text{delay}}$ is only 3 dB for $\tau_r = 50$ ns and 2 dB for $\tau_r = 70$ ns.

D. Influence of the sampling factor $f_s$

$F_{\text{delay}}$ increases slightly for increasing $f_s$. E.g., when changing $f_s$ from 1 to 4, there is an increase of $F_{\text{delay}}$ by 0.6 dB for $\tau_r = 200$ ns and 2.5 dB for $\tau_r = 50$ ns.

IV. IMPLICATIONS TO OFDM DESIGN

Our analysis shows that, to suppress the noise factor $F_{\text{delay}}$ due to delay spread, an efficient strategy is related to the increase of the cyclic prefix length $CP$ (i.e., guard interval (GI)). When switching to a long GI option of 1600 ns (from 800 ns GI), $F_{\text{delay}}$ is reduced by even 17.4 dB for $\tau_r = 200$ ns, and by 24.8 dB for $\tau_r = 140$ ns. The data rate $R_{\text{data}}$ is reduced by 17%, but this is largely compensated by the strong reduction of $F_{\text{delay}}$.

The strategy of an increased CP is easy with respect to the implementation, but the theoretical data rate $R_{\text{data}}$ is reduced. To keep this data rate constant, the ratio between $P$ and $CP$ should be kept constant. As mentioned before, this requires a higher hardware complexity. However, in systems with a higher bandwidth mode, such as 802.11n (40 MHz) and 802.11ac (40/80/160 MHz), the more complex hardware could be combined with the principle of scaled OFDM [5]. This would provide a method for systems with a higher bandwidth mode to implement a long GI option for a lower bandwidth mode, without reduction of the (theoretical) data rate and without requiring a complex hardware extension.

V. CONCLUSION

In this work, the performance loss due to delay spread (in terms of $F_{\text{delay}}$) has been analyzed as a function of OFDM parameters for a wide range of reverberation time (i.e., 10 – 200 ns). This loss, caused by diffuse multipath, can be severe: e.g., $F_{\text{delay}} = 38.6$ dB for $CP = 800$ ns, a 30 dBm transmit power and a high (but realistic) $\tau_r = 140$ ns. $F_{\text{delay}}$ decreases exponentially with increasing $CP$. E.g., for $\tau_r = 140$ ns, there is a reduction of $F_{\text{delay}}$ by about 25 dB, when switching $CP$ from 800 ns to 1600 ns. Further, we found that $F_{\text{delay}}$ decreases inversely proportionally with increasing $P$. Taking into account the implications on the theoretical data rate and the hardware complexity, we propose to adopt a long guard interval option to the 802.11 OFDM standard to ensure reliable reception in high multipath environments. In future research, the analysis presented will be validated experimentally.

REFERENCES