Link-Layer Retransmissions in IEEE 802.11g based Industrial Networks

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Abstract

Characterization of the behaviour of link-layer retransmissions is helpful when designing MAC protocols and scheduling algorithms for Factory Automation WLANs. In this paper, we measure retransmission rates and consecutive retransmission occurrences of IEEE 802.11g communication links in an industrial indoor environment. The employed wireless channel at 2.4 GHz is characterized. Experimental results show that the distribution of consecutive retransmission occurrences tends to concentrate around just one retry when devices operate within their transmission range. It is also shown that smaller frames result in fewer retransmissions.

1. Introduction

Due to the success of IEEE 802.11 networks in home, office and other environments, deployment of IEEE 802.11 networks in industrial halls has already begun. However, their application in real-time control remains a challenge due to the lack of both, reliability and ability to meet real-time requirements. Wireless communication links are prone to communication errors due to the time-varying nature of the wireless channel. Propagation's path loss, shadowing, multipath and interference [1] cause bit errors that, in turn, result in frame errors. The uncoordinated medium access (collisions) also causes information loss. To enhance reliability, IEEE 802.11 networks utilize Forward Error Correction (FEC) and Automatic Repeat Request (ARQ) mechanisms [2]. In FEC, redundant information is added to data frames, so that the receiver is able to detect and correct bit errors. The ARQ mechanism is based on feedback from the receiver. Retransmissions of the whole data frame occur when errors, that FEC was not able to correct, are detected. Retransmissions continue until the frame is successfully delivered or until a retry limit has been reached.

This paper presents results from measurements in a real industrial automation environment. Frame retransmission rates and the distribution of consecutive occurrences have been derived from all experiments. Additionally, a channel characterization, in terms of impulse channel response

and transfer function, is presented. The remainder of the paper is organized as follows. Section 2 discusses the related work. In Section 3 the measurement setup is discussed along with the characterization of the 2.4 GHz industrial wireless channel and the experimental results are presented. We conclude the paper in Section 4.

2. Related Work

In [3] measurements to investigate the impact of retransmissions on TCP performance were carried out in an office environment. The results show that the reverse channel (transmission of acknowledgment frames) presents error rates as high as those from the forward channel (transmission of data frames). The effect of retransmissions on multimedia traffic was studied in [4]. The emphasis was placed on the channel access originated interference rather than on the wireless channel itself. In [5] impulse response measurement results for the 2.4 GHz ISM band in an indoor industrial environment are presented, showing that the delay spread is much higher compared to office environments. Bit error measurements of an industrial wireless channel with 802.11 communication are found in [6]. A methodology and software tool for channel measurements is presented in [7]. As an example, the authors used an 802.11a WLAN link in an industrial environment. It was qualitatively confirmed that a 802.11a deployment in certain industrial applications should be basically feasible. However, there is to the best of our knowledge no work that presents results of link-layer retransmissions behaviour for IEEE 802.11g networks in a real industrial automation environment with industrial real-time traffic flows considering the impact of frame size, data rate and obstructions in the communication path.

3. Empirical Evaluation

In the following sub-sections, the environment, settings, performance metrics and results of the empirical evaluation are described.

3.1. Measurement Setup

Measurements are carried in a real factory shop floor for automated furniture manufacturing. It has a main corridor and a number of different machines disposed as work cells. The ceiling, made out of metal and acrylic, is approximately 15 meters high. The shop floor area is separated by walls and thick glass from office space. The layout is shown in Fig. 1.

Figure 1. Industrial environment for the measurement setup

The experimental testbed includes two IEEE 802.11g compliant industrial-grade radios [8], one working as an Access Point (AP) and the other one as a client (STA). Both devices were attached to a static mounting pole at a height of approximately 1.5 meters from ground with one 5.0dBi gain omnidirectional antenna each. Some objects and people, around the devices, were in motion during the measurements. In the case of *line of sight* (LOS) measurements, however, neither objects nor people obstructed the direct path between the antennas of the devices. Transmit power was set to the highest possible level, which is provided by the manufacturer. The devices have a default retry limit setting of 7 (the original frame plus up to six retransmissions). The Ethernet ports (100BaseT) of both devices were connected to an AnritsuTM network data analyzer (model MD1230B) that was used to generate Ethernet frames periodically, according to a selected service interval, and record the received Ethernet frames that have passed through the wireless system. Additionally, all data, management and control frames, were captured using a wireless monitor (WM). The WM was carefully collocated next to the STA ensuring that all data frames and their retransmissions were captured. This is corroborated by comparing trace files generated by the WM, with trace files from the network analyzer. Having just one client and only one traffic flow allows to isolate communication errors due to the channel access mechanism. In this way, the only source of errors that has an influence on the results is the wireless channel.

The measurement scenarios use the following settings:

- WLAN technology: IEEE 802.11g

- Frame size: 64, 128, 256 and 1518 *bytes*
- Service interval: 10, 30 and 50 *ms*
- Data rate (modulation and coding rate [2]): 6, (BPSK, 1/2) 12, (QPSK, 1/2) or 54Mbps, (64-QAM, 3/4)
- Path: 15 m *LOS* and 20 m *NLOS*

The measurements ran for 60s for every trial and data tracing began only after both, AP and STA were associated.

The *retransmissions rate* is calculated according to (1). This value provides the rate of retransmissions to data frame transmissions.

$$\text{RetransmissionRate} = \frac{\text{Retransmissions}}{\text{SentFrames}} * 100\% \quad (1)$$

The other performance metric, that is derived from the experiment, is the distribution of occurrences for consecutive retransmissions. This information is extracted from trace files obtained by the WM. The files are parsed and filtered to identify data frame transmissions and retransmissions, if any, for each data frame. The number of retransmissions that occurred, for each data frame that needed them, is reported.

3.2. Industrial Channel Characteristics

One of the main differences of an industrial RF channel, in comparison to office environments, is the increased multipath effect caused by metal elements, heavy machinery and several moving objects. Multipath propagation results in a frequency selective behaviour of the channel, which makes it less reliable. RF channels are characterized by a time-varying impulse response $h(t, \tau)$ and their corresponding transfer function $H(t, f)$. The previously described industrial environment for the measurement setup has been analyzed with respect to $h(t = t_0, \tau)$ and $H(t = t_0, f)$. For the sake of simplicity both are time-invariant and stationary, since the environmental conditions had been rather motionless during the measurements. In a previous work [9] measurements within the same industrial environment have already been conducted. A vector network analyzer (VNA) was used for measuring the transfer function of the *LOS* and *non line of sight* (*NLOS*) channel. These results are used to characterize the channel for the *LOS* and the *NLOS* links.

The impulse response for the *LOS* channel, with highlighted statistical parameters, is shown in Fig. 2 (a). In the time domain, the mean excess delay $\bar{\tau}$ and the delay spread τ_{RMS} are derived from the impulse response $h(\tau)$ [1]. The mean excess delay is defined in (2).

$$\bar{\tau} = \frac{\int_0^{\infty} \tau |h(\tau)|^2 d\tau}{\int_0^{\infty} |h(\tau)|^2 d\tau} \quad (2)$$

Figure 2. (a) Impulse response $h(\tau)$ and (b) Transfer function $H(f)$ of the industrial environment

The delay spread is a measure of the multipath spreading within the RF channel and defined as

$$\tau_{RMS} = \sqrt{\tau^2 - (\bar{\tau})^2}, \quad (3)$$

where

$$\bar{\tau}^2 = \frac{\int_0^{\infty} \tau^2 |h(\tau)|^2 d\tau}{\int_0^{\infty} |h(\tau)|^2 d\tau}. \quad (4)$$

The mean excess delay $\bar{\tau}$ is mainly determined by the transmission range and the environment's multipath profile. An environment with significant multipath effects leads to a slowly decaying $h(\tau)$ and a large τ_{RMS} , which is the case for industrial channels (cf. Fig. 2 (a)). Office and residential environments are characterized by a much smaller delay spread.

In Fig. 2 (b) the transfer function is shown. Analog to the delay spread in the time domain, the coherence bandwidth B_c characterizes the channel in the frequency domain. It is a statistical measure for the frequency range over which the channel can be considered as "flat", and is derived from the frequency correlation function. The *median* of the transfer function indicates the median attenuation and depends primarily on the distance of the transceivers. Based on the cumulative distribution function (CDF) of $H(f)$ the two limits H_{10} and H_{90} can be determined leading to ΔH , which is the frequency selective fluctuation of the channel. 80% of the values are within this interval. Both limits are relative to the *median*.

The statistical parameters of both channels are summarized in Tab. 1. The *median* of the *NLOS* channel is lower, due to an increased attenuation and the frequency-selective variation, characterised by higher value of ΔH . Furthermore, slightly higher time dispersion parameters are computed. In summary it can be concluded that the *NLOS* channel is worse compared to the *LOS* link.

In addition to this, the whole spectrum was very crowded, due to a large installed base of devices operat-

Table 1. Statistical parameters industrial channels (*LOS* and *NLOS*)

Parameter	<i>LOS</i>	<i>NLOS</i>
$\bar{\tau}$	119.19ns	157.11ns
τ_{RMS}	78.15ns	82.08ns
B_{c50}	3.5MHz	2.5MHz
<i>median</i>	-62.45dB	-67.59dB
ΔH	13.33dB	14.2dB
H_{90}	4.56dB	5.62dB
H_{10}	-8.77dB	-8.58dB

ing at 2.4GHz. The noise level was recorded to have an average value of $-85dBm$.

3.3. Results

The results for the 802.11g experiments show that the performance is consistent across all scenarios (see Tab. 2). In fact, retransmission rate values for *NLOS* at 54Mbps are as low, if not lower, than *LOS* at 6Mbps. An explanation of this phenomena might be that the industrial channel might differ depending on the current environmental conditions. Frames with the smallest payload size always have lower retransmission rates than the largest ones.

Consecutive retransmission occurrences for 802.11g with *LOS* and *NLOS* (at a data rate of 54Mbps) are shown in Figs. 3 (a) and 3 (b) respectively. The service interval is 10 ms. In both graphs a trend of greater number of retransmissions as the frame size increases can be observed. Moreover, the distribution of retransmissions for both 802.11g links is concentrated on one or, seldom, two retransmissions and not evenly distributed across the number of retries.

4. Conclusion

In this paper, IEEE 802.11g link-layer retransmissions have been measured. The wireless indoor channel (2.4 GHz) of the industrial test environment has been characterized in terms of its impulse response $h(\tau)$ and its trans-

Table 2. Retransmission rates for IEEE 802.11g experiments. All results displayed are in %

Scenario	Payload (bytes)	Data Rate = 6Mbps			Data Rate = 12Mbps			Data Rate = 54Mbps		
		SI=10ms	SI=30ms	SI=50ms	SI=10ms	SI=30ms	SI=50ms	SI=10ms	SI=30ms	SI=50ms
LOS	64	1.93	3.66	5.28	1.26	1.35	0.85	0.53	0.71	0.43
	128	3.38	5.11	6.66	1.68	1.56	1.97	0.79	1.14	1.15
	256	5.35	5.59	5.65	2.33	2.52	1.49	1.38	2.27	1.43
	1518	5.09	6.26	7.77	3.83	2.77	3.57	3.78	4.58	3.61
NLOS	64	1.96	1.15	1.53	1.34	1.10	1.10	1.10	1.05	1.23
	128	0.18	1.63	1.63	1.90	1.36	1.11	1.06	0.95	1.07
	256	2.45	2.72	4.41	4.61	2.34	3.29	1.04	1.37	2.05
	1518	4.22	4.22	3.17	4.86	4.48	3.20	2.10	4.11	2.57

Figure 3. Distribution of retransmission occurrences for LOS and NLOS, IEEE 802.11g, 54Mbps

fer function $H(f)$. Its common statistical parameters, such as *delay spread*, *mean excess delay* have been derived. Retransmission rates and occurrences of consecutive retransmissions in IEEE 802.11g networks, measured in a real industrial environment, have been presented. It has been shown that the selected data rate, LOS vs. NLOS communication and frame size affect the total number of retransmissions experienced during a period of time. As expected, frames with smaller payload sizes have always lower retransmission rates than larger frames. Furthermore, most of the observed occurrences are of one consecutive retransmission, seldom two or three. The information presented in this paper is particularly relevant for error recovery resource estimation in IEEE 802.11-based networks that use a contention-free medium access mechanism (because the experiments did not include errors derived from the contention-based channel access). These results provide a guideline of how often retransmission efforts for a traffic stream will be needed and how many retransmissions will be required to successfully deliver a frame that belongs to that traffic stream. Our future work will focus on describing the impact of retransmissions on real-time performance (delay) and on using this information in designing error recovery mechanisms for factory automation WLANs. It is planned to develop a new link-layer retransmission policy, which satisfies real-time application requirements. Therefore, a mechanism able to control the retransmissions, using information about the resources that have to be allocated for error recovery, is required to improve the performance of real-time industrial communication applications.

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