Estimating the cause of frame losses in 802.11 wireless networks

Morihiko Tamai\textsuperscript{a)}, Akio Hasegawa, and Hiroyuki Yokoyama

Adaptive Communications Research Laboratories, Advanced Telecommunications Research Institute International, Kyoto 619–0288, Japan

\textsuperscript{a)} morihit@atr.jp

Abstract: In indoor wireless environments such as warehouses and factories, since radio propagation occurs in complicated ways and there are large moving objects like Automated Guided Vehicles (AGVs), from the perspective of network management, maintaining wireless communication quality is challenging. Because the failures in wireless communications may lead to undesirable delay or even stop in the manufacturing processes, it is desirable not only to detect degradations in link quality, but also to estimate the cause of the frame losses, to recover from the link failures as quick as possible. In this paper, we propose a sensing system that allows comprehensive analysis between physical and Medium Access Control (MAC) layer information, and allows estimation of the cause of the frame losses due to signal attenuation or interference. We implemented a prototype sensor node using an FPGA board and conducted an experiment to investigate the accuracy of the estimation. From the experiment, we confirmed that the prototype sensor node can determine whether the cause is due to attenuation or interference with high accuracy.

Keywords: wireless LAN, sensing system, cross layer

Classification: Network Management/Operation

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1 Introduction

Internet of Things (IoT) devices are recently deployed rapidly to the indoor environments such as warehouses, factories, hospitals, and malls [1, 2]. By introducing the IoT devices to these environments, it is expected that the various operations such as monitoring of the environmental data and device conditions, industrial automation, and maintenance are facilitated. On the other hand, in such environments, since signal attenuation and interference occur in complex and unpredictable manner, it is difficult to ensure the network stability. From the perspective of network management in such challenging environments, it is not enough just to detect the degradations in link quality, and is desirable to estimate the cause of the link failures, to recover from the performance degradations quickly. Signal attenuation and interference are the two of the major causes of the frame losses in the indoor environments. For example, in factories, signal attenuation will occur due to various moving objects such as AGVs. Moreover, since the indoor radio propagation is complicated, interference due to the hidden terminal situation will occur easily.

The information mainly related to the physical layer (called physical layer information) and the information mainly related to the MAC layer (called MAC layer information) are the information useful for assessing wireless link quality. The typical examples of acquiring these information are spectrum analysis [3] (physical layer information) and packet capture [4] (MAC layer information). Spectrum analysis allows the users to know that how much congestion is occurring in the target frequency band, how strong the radio signals arrive, etc. Packet capture allows the users to know that which nodes are communicating, what kind of control frames are transmitted, etc. In the existing schemes or products, physical layer information and MAC layer information are often acquired and analysed individually [3, 4]. However, as given in the above examples, since each layer contains information that is difficult to be acquired from the other layer, by acquiring and analyzing both simultaneously, it seems that we can perform more detailed assessment on the wireless link quality. Specifically, in this paper, we focus on the estimation of the cause of the frame losses due to signal attenuation or interference. It is possible to detect the occurrence of the frame losses by analysing the result of packet capture easily. However, it is difficult to estimate the cause of the frame losses from only the packet capture data. By combining information both from physical and MAC layers, we propose the procedure that determines the cause of frame losses accurately.

2 System overview

We suppose that multiple IoT devices are deployed in the target environment (e.g., factory) and they are communicating via IEEE 802.11 wireless LANs. To collect physical and MAC layer information, we introduce a sensing system that consists of multiple sensor nodes and an analysis node. Fig. 1 shows the module structure of a sensor node. Each sensor node is tuned to receive the radio signals transmitted by the IoT devices, acquires In-phase and Quadrature-phase (IQ) data, which is a time series of signals to be demodulated, and generates two types of data from the IQ
data: (i) a time series of signal strengths (called *envelope data*, hereafter) and (ii) a time series of information extracted from each MAC header (called *header data*, hereafter), which is acquired by parsing the demodulated bit sequence based on the IEEE 802.11 specification. An envelope data and a header data fall into the categories of physical and MAC layer information, respectively. Both data are acquired on each sensor node simultaneously and continuously, and uploaded to the analysis node. One naive approach to acquiring both the physical and MAC layer information is that connecting both a Software Defined Radio (SDR) device and an off-the-shelf Wi-Fi interface to a sensor node, and calculating the signal strengths from the IQ data sampled by the SDR device and executing packet capture on the Wi-Fi interface. However, in this approach, it is difficult to maintain time synchronization between physical and MAC layer information. By generating the envelope data and the header data from the same IQ samples as shown in Fig. 1, we can synchronize between physical and MAC layer information easily. In this paper, we assume that the time synchronization between sensor nodes is achieved by using a time synchronization protocol such as Precision Time Protocol (PTP). By collecting sensory data from the sensor nodes, the analysis node can observe multiple data on an identical time axis and perform estimation procedure to be described in the next section.

3 Estimation of the cause of frame losses

In this section, we explain how to estimate the cause of the frame losses by analysing the envelope data and the header data acquired from multiple sensor nodes. We use an example shown in Fig. 2(a). In the figure, we consider the situation where data frames are sent from device B to the device A, and the first transmission is succeeded and the second transmission is failed due to signal attenuation (Fig. 2(b)) or interference (Fig. 2(c)). We suppose that the sensor node 1 and 2 are located near the device A and B, respectively. The procedure for estimating the cause of the frame losses (i.e., attenuation or interference) is as follows:

**Step. 1** First, we collect the data from the sensor nodes located near the sender side (sensor node 2 in the example) and near the receiver side (sensor node 1 in the example), respectively.

**Step. 2** Next, we find the header data that is contained in the set of the header data acquired at the sender side, but is not contained in the set of the header data acquired at the receiver side. For example, in Fig. 2(b) and (c), the header data that corresponds to $h_{2,1}$ is not contained in the set of the header data acquired by sensor node 1.
Step. 3 For each header data found in Step. 2, we find the enveloped data that has an intersection on the time axis from the set of the envelope data acquired at the receiver side. For example, in Fig. 2(b) and (c), $e_{1,1}$ has an intersection with $h_{2,1}$ on the time axis (i.e., $\text{time}(e_{1,1}) \cap \text{time}(h_{2,1}) \neq \emptyset$, where $\text{time}(\cdot)$ represents the time range of the data).

Step. 4 Lastly, each pair of the header data $h$ found in Step. 2 and the enveloped data $e$ found in Step. 3, we calculate the absolute value of the difference between $\text{time}(e)$ and $\text{time}(h)$, and compare the value with the predefined threshold $t_{\text{thr}}$. If $|\text{time}(e) - \text{time}(h)| \leq t_{\text{thr}}$ holds, then we conclude that the cause of the frame loss is due to attenuation, otherwise, we conclude the cause is due to interference.

4 Implementation

We implemented a prototype sensor node, which consists of a RF transceiver (AD9371), an FPGA (Kintex), a SoC (Zynq), an ordinary PC, and antennas. The target frequency of the RF transceiver is 2.4 GHz band. The FPGA generates IQ data whose sampling rate is 20 MS/s. The envelope data is generated by calculating the signal strength of each IQ sample by the formula: $S = 10 \log_{10}(I^2 + Q^2)$, where $S$ is the signal strength, and $I$ and $Q$ are 16 bit integers that represent values of an I component and a Q component of an IQ sample, respectively. The envelope data is transferred directly from the FPGA to the PC via a 10 Gigabit Ethernet interface. The FPGA also performs the demodulation based on the IEEE 802.11b/g standard, and the demodulated bit sequence is transferred to the SoC. Then, SoC generates
the header data using the libpcap [5] library and transfers the header data to the PC via a Gigabit Ethernet interface. Then, the PC transfers the envelope and the header data to the analysis node.

5 Experiment

To investigate the effectiveness of the estimation method described in Section 3, we conducted an experiment that measures the accuracy of the estimation. In the experiment, we prepared the controlled environments where the frame losses occur due to signal attenuation (called environment 1) or interference (called environment 2) by connecting between sender, receiver, and sensor nodes with RF cables and attenuators. The details of the each environment is as follows:

Environment 1 One sender node, one receiver node, and two sensor nodes (each of which is located near the sender or the receiver node) are deployed. The sender node transmits an UDP broadcast frame with 1000 bytes payload at the data rate of 6 Mbps once in 10 ms. The attenuator between the sender and the receiver is adjusted so that the receiver node can not decode the frames successfully due to signal attenuation. Fig. 3(a) shows an example of envelope data acquired at the receiver side sensor node and the lost frames identified by Step. 2 of the procedure described in Section 3. From the figure, we can see that the frames are lost at the receiver node due to signal attenuation.

Environment 2 Two sender nodes (called data sender and interferer), one receiver node, and two sensor nodes (each of which is located near the data sender or the receiver node) are deployed. The Data sender transmits an UDP broadcast frame with 1000 bytes payload at the data rate of 6 Mbps once in

![Figure 3](image-url)

**Fig. 3.** Example of the envelope data (blue rectangles) acquired at the receiver side sensor node and the lost frames identified (green rectangles) by the Step. 2 in the procedure describe in Section 3.
10 ms. The interferer transmits an UDP broadcast frame with 1200 bytes payload at the data rate of 1 Mbps once in a random period sampled from the normal distribution with mean 15 ms and standard deviation 5 ms. The attenuators between the two senders are adjusted so that each sender do not detect ongoing transmission by the other sender. Fig. 3(b) shows an example of envelope data acquired at the receiver side sensor node and the lost frames identified. From the figure, we can see that frames are lost at the receiver node when the interfering signals are overlapped.

For each environment, the set of envelope data and the set of header data are acquired from the sensor nodes during the period in which 100 frame losses are recorded. Then, for the total of 200 instances of the frame losses, the cause of the frame loss of the each instance is determined using the procedure described in Section 3. In this experiment, we set $t_{thr}$ to 10 microseconds. From the experiment, we confirmed that the causes of the frame losses of the all 200 instances are estimated correctly.

6 Conclusion

In this paper, we showed that, by combining the information both from the physical and MAC layers, it is possible to estimate the cause of the frame losses due to attenuation or interference with high accuracy. In the future, we focus on more detailed evaluation of the proposed estimation method by deploying the sensing system in the actual environments and acquiring the data from the communications among actual IoT devices.

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