Performance Analysis of Parallel Redundant WLAN

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Abstract

The application of the "Parallel Redundancy Protocol" (PRP) according to IEC 62439-3 with two diverse redundant wireless channels achieves an improved overall wireless communication channel. Performance parameter like jitter and reliability increase significantly compared to the single wireless channels. In this work, a series of measurements on a redundant setup with two parallel WLANs according to IEEE 802.11n in diverse configuration settings is conducted and the results presented. A Markov model for the parallel redundant system is developed and the analytical results compared against the measurements.

1. Introduction

IEEE 802.11 [1] (WiFi) is widely used for wireless local area networks (WLANs) and as a part of the IEEE standards family, easily interoperates with 802.3 (Ethernet) LANs. This was an important factor towards establishment of 802.11 as an industry accepted solution.

On the other side, wireless transmission is known to be error-prone and its error characteristics behave time-variable and non-deterministic. This labels wireless communication as not very well suited for industrial applications with tight reliability requirements, such as guaranteed maximum latency times for packet transmission.

Diversity as a redundancy technique is a well-known countermeasure to improve performance characteristics of wireless communication systems on a stochastic basis. Brennan's classical 1959 paper [2] concisely describes the basic diversity approaches for wireless communication systems, which are space, time, frequency and polarisation diversity.

The IEEE 802.11 family of standards specifies the characteristics of both the physical (PHY) and medium access control (MAC) layers. At the physical layer, 802.11 provides multiple options for the creation of transmission diversity in a redundant system.

In [3], we utilized the "Parallel Redundancy Protocol" (PRP) according to IEC 62439-3 [4] as diversity combination method on the wired Ethernet interfaces of two independent and diverse IEEE 802.11 WLAN channels to operate two point-to-point links in parallel. We investigated whether this system can form a reliable *black channel* suitable for safety applications under certain timing constraints. It could be demonstrated that the system (see Figure 1) achieved a significant increase in availability compared to a single WLAN channel. Additionally some latency and jitter measurements on the safety protocol packet transmission level proved a great improvement also on these performance parameters [3].

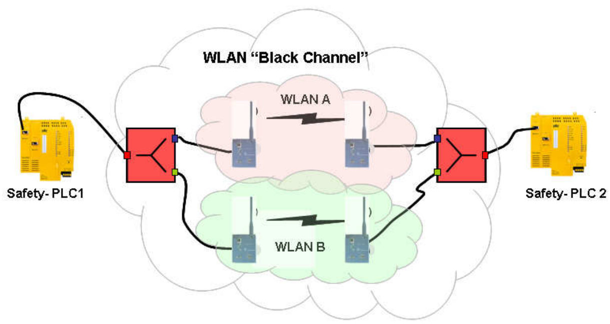

Figure 1. Parallel Redundant WLAN with Safety Application [3]

In this subsequent work, we conduct a more detailed performance analysis to gain a deeper insight into the performance behaviour of such a parallel redundant WLAN system. This time we focus on Ethernet packet transmission behaviour, not safety application protocol behaviour as in [3].

Measurements with different traffic patterns on Ethernet packet level are collected to gain a representative statistical basis. The measured results from these experiments are then compared to the computed results from a theoretical Markov model.

The main purpose of building such a parallel redundant WLAN system is to achieve an improvement in certain performance characteristics. Thus we define improvement factors for these specific characteristics to later be able to highlight the application areas of highest efficiency for the parallel redundant WLAN approach.

The paper is structured as follows: In chapter 2, the operational principle of parallel redundant WLAN with PRP is briefly explained. Chapter 3 gives an overview on performance analysis methods for WLAN, defines performance parameters of specific interest for Industrial WLAN and presents an availability model. In chapter 4, the parallel redundant WLAN system is modeled with a Markov chain. In chapter 5, a measurement setup and measurement algorithm is described. Chapter 6 presents the measurement results and chapter 7 discusses the simulation results. Finally, chapter 8 concludes on the findings and the possible further work.

2. Parallel Redundant WLAN

Fault-tolerance or **graceful degradation** enables a system to continue operating properly in the event of the failure of some of its components. Fault-tolerant systems must provide no single point of failure, which is typically achieved with redundant components or communication paths, depending on the type of system.

The basic idea behind diversity in communications technology is redundant transmission of information over uncorrelated (stochastically independent) channels that only with a small probability are erroneous at the same time window.

Diversity methods are usually applied on the radio frequency (RF) level of a wireless system to combat small-scale or multi-path fading behaviour over short periods of time, commonly modelled as Rayleigh [5]. A generic wireless diversity system is depicted in Figure 2.

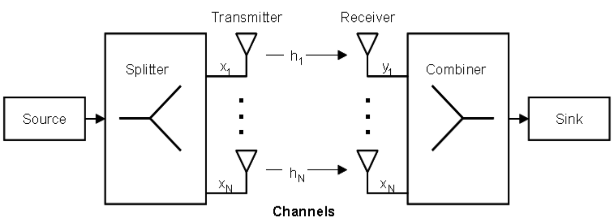

Figure 2. Wireless Diversity System

2.1. Parallel Redundancy Protocol

A PRP network consists of two separate LANs (LAN A and LAN B) with arbitrary, but similar topology. Each PRP node has two Ethernet interfaces connected to one of the two LANs and transmits data simultaneously over the two interfaces into both networks, tagging each frame with a four octets Redundancy Control Trailer (RTC) containing identical sequence numbers. The sequence number is incremented for each frame pair sent. The first arriving frame of a pair is accepted by the PRP receiver node and the second frame gets discarded. As long as one of the two LANs is operational, one of the duplicated frames always reaches its destination.

To use the PRP redundancy capability, non-PRP nodes must be attached through a Redundancy Box (*Red Box*), which is a device that behaves like a DAN. A Red Box functionality from ZHAW [6] and its simplified schematic is depicted in Figure 2.

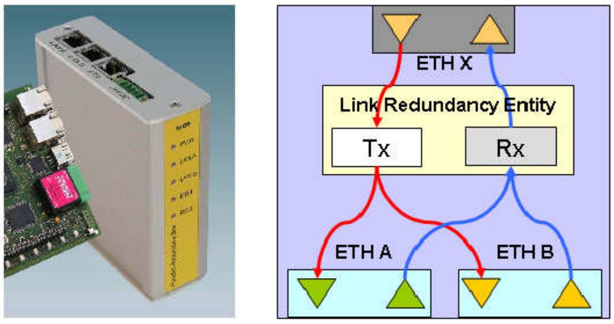

Figure 3. PRP Redundancy Box: An Ethernet splitter and selection combiner

The PRP Red Box can be at the receiving side modelled as a post-detection **selection combiner** [2], where out of the two branches the "better" signal is selected and further processed, in this case the first arriving Ethernet packet. The second arriving packet is discarded. Thus we name this type of combiner a "**timing combiner**", since a significant performance improvement is gained through this timing behaviour.

Applying two *RedBoxes* against each other allows the creation of a diverse 1oo2 (1-out-of-2) system on the Ethernet level. In this work, we use two WLAN point-to-point links as WLAN A and WLAN B, forming a parallel redundant WLAN with PRP as splitter and combiner (see Figure 1). This multi-radio diversity architecture applies several of the basic diversity techniques to improve the overall quality of the combined wireless channel.

3. Performance Analysis

As presented in an overview in [7], most published works on the performance of IEEE 802.11 networks focus on throughput, both theoretically and experimentally.

An experimental performance measurement campaign in an outdoor scenario has been presented in [8]. The experiment in [9] compares the measured packet loss ratio of 802.11a and 802.11g WLANs on commercial products. In [10], both unicast and multicast real-time transmissions were investigated in an indoor scenario, whereas in [11] the transmission performance of video data was compared on 802.11e and 802.11n. The experiment in [12] compared the throughput performance of 802.11n in an office environment and an anechoic chamber.

In [3] and [13], the measurements focused on reliability, latency and jitter, which we consider as the most important criteria for industrial communication systems. In our analysis of the parallel redundant WLAN system, we will focus on the criteria defined below.

3.1. Performance Parameter

For performance estimation of a communication system, parameters related to traffic behaviour as directly influencing the end application are important. We consider the following as of specific interest:

Latency is measured as the unidirectional packet transmission time over the communication system.

Jitter as latency variability is computed from the latency measurement samples.

Packet Loss is measured on the Ethernet level of the communication system.

Throughput is measured as the unidirectional packet transmission capability over the communication system.

3.2. Reliability Parameters

For industrial applications with tight real-time and availability requirements, a reliability estimation of the parallel redundant wireless system is of specific importance. System availability over its life-cycle is typically determined as a factor of its reliability.

In [3] we have analysed system reliability related to the safety applications duty cycle time. The goal was to find the boundary where the system is still functioning with sufficient availability for the safety application.

To clearly distinguish towards reliability engineering approaches related to hardware availability that are often found in literature [15][16], we define the following for our availability model (see Figure 4):

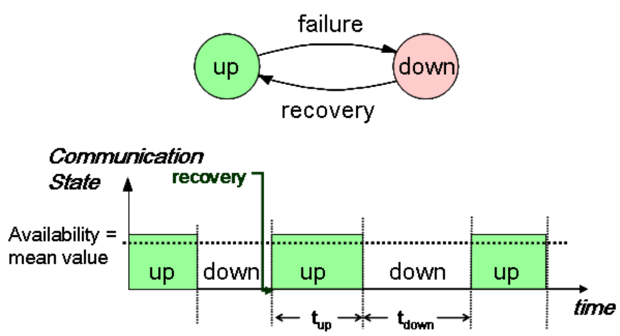

Figure 4. Availability Model

Mean Time To Failure (MTTF) expresses the mean time when the communications system is able to process its data traffic without packet loss on the Ethernet level.

Mean Time To Recovery (MTTR) expresses the mean time when the communication system is experiencing packet loss on the Ethernet level.

Availability *A* expresses how often the system is functioning over its life-cycle, depending on *MTTF* and *MTTR*.

$$A = \lim_{t \to \infty} \frac{\sum t_{up}}{\sum (t_{up} + t_{down})} = \frac{MTTF}{MTTF + MTTR} \quad (1)$$

The *failure rate* λ and *recovery rate* μ are determined as follows:

$$\lambda = \frac{1}{MTTF} \quad (2)$$

$$\mu = \frac{1}{MTTR} \quad (3)$$

Unavailability *U* can express the probability of a system outage over its life-cycle more comfortable in time units:

$$U = (1 - A) \quad (4)$$

To gain representative values for the non-deterministic wireless communication system, the collection of data samples over longer observation periods is required.

3.3. Improvement Factors

For performance estimation of the parallel redundant wireless system, the computation of improvement factors for the previously described basic performance criteria can be of specific interest.

Improvement Factor (IF) is here yielded by the combination of the performance values of the two single channels P_A and P_B, compared against the overall channel P_X. A generic improvement factor P_{IF} for the parallel redundant system can be calculated according to the following equation, comparing the mean value of the single channels against the overall channel:

$$P_{IF} = \frac{(P_A + P_B)}{2P_x} \quad (5)$$

P is to be substituted for the performance parameter to be investigated. The order of the values is chosen so as to obtain a ratio greater than one.

An alternative method would be to compare the best performing of the two single channels with the overall channel:

$$P_{IF} = \frac{P_x}{MAX(P_A, P_B)} \vee \frac{MIN(P_A, P_B)}{P_x} \quad (6)$$

This approach can be likely more suitable, since possible performance degradations with the parallel redundant approach against the better performing single channel become clearly visible.

4. Markov model

To calculate the reliability and availability of repairable 1oo2 (1-out-of-2) systems [15][16], Markov modelling (Figure 5) is widely used in reliability engineering. However, in our context it must be considered that random *failure* is clearly a Markov process, whereas the commonly used property *repair* is not necessarily a stochastic Markov process. Failures are events that occur at random points in time, whereas repairs occur deterministically either immediately after failure or at fixed maintenance intervals on systems with standby redundancy.

The active redundancy based parallel WLAN system with PRP selection combining can be correctly modelled as Markov chain only when *repair* is also a random property. To indicate this, the commonly used term "repair" was replaced by "recovery". Thus failures are regarded as transient due to environmental influences and are also autonomously reversible if environment changes. As already stated, for our system *MTTF* is defined as the average duration between packet loss events within the observation period whereas *MTTR* is the average duration of these packet loss events. For our Markov model, we need to define the *failure probabilities* P_f and *recovery probabilities* P_r of the single WLAN channels per Ethernet packet, and with (2) we yield $P_f = \lambda/n$, where n represents the number of measured Ethernet packet samples.

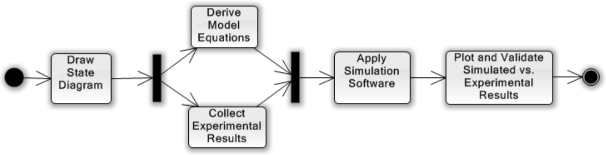

Figure 5. Markov Modelling Method

Figure 5 shows an activity diagram on applying Markov modelling. Initially, a state diagram is drawn, then the equations are derived to describe the transition probabilities between the states. Actual transition probabilities can be collected with an experimental measurement setup. Some of these experimental results are applied as input to a numerical analysis program, and the computed results compared with other experimental results. Upon match, the model is proven to be applicable.

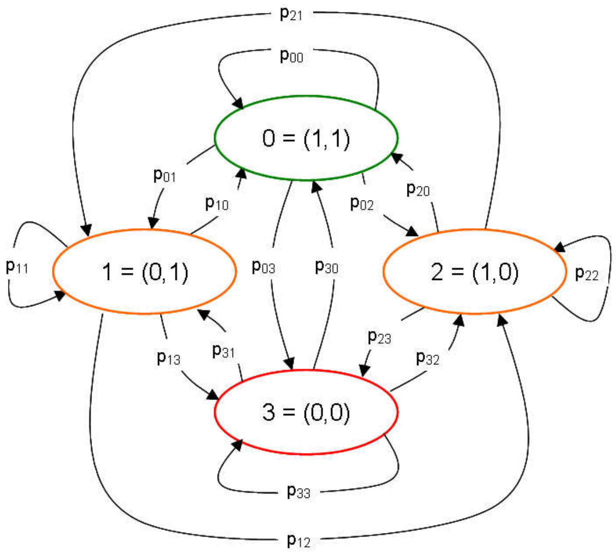

Figure 6. Markov Model for 1oo2

In our Markov model (Figure 6), the link state is defined as S = (i,j), where i is the status of WLAN A (1 = up, 0 = down) and j is the status of WLAN B (1 = up, 0 = down). State (1,1) represents a correct functionality of both single WLANs. State (0,1) and (1,0) represent a failure in WLAN A or WLAN B. Finally state (0,0) represents a simultaneous failure in both WLANs and therefore also in the overall PRP system.

We have a Discrete Time Homogeneous Markov Chain (DTMC) with state-space S = {0, 1, 2, 3} and time parameter set T = $\{t_0, t_1, \ldots t_n\}$ with cycle time = $t_n - t_{n-1}$. Thus in every transmitting cycle a transition is possible with countable number of time parameters (n+1), which is a condition for a DTMC. The probability of a transition from state i to state j is called *transition probability* p_{ij}. Due to error bursts in WLAN systems, we differentiate between *failure probability* without (P_f) and with a foregoing failure ($P_{f'}$). This yields the *recovery probability* P_r as follows:

$$P_r = 1 - (P_{f'}) \tag{7}$$

The transition matrix P is described as:

$$P = \begin{bmatrix} p_{00} & p_{01} & p_{02} & p_{03} \\ p_{10} & p_{11} & p_{12} & p_{13} \\ p_{20} & p_{21} & p_{22} & p_{23} \\ p_{30} & p_{31} & p_{32} & p_{33} \end{bmatrix} \tag{8}$$

With failure probabilities P_{fA}, $P_{fA'}$ for WLAN A and P_{fB}, $P_{fB'}$ for WLAN B, all p_{ij} can be described:

$$\begin{aligned}
p_{00} &= 1 - (p_{01} + p_{02} + p_{03}) = 1 - (P_{fA} + P_{fB}) \\
p_{01} &= P_{fA} - (P_{fB} * P_{fA} * P_{fB} / (P_{fA} + P_{fB})) \\
p_{02} &= P_{fB} - (P_{fA} * P_{fA} * P_{fB} / (P_{fA} + P_{fB})) \\
p_{03} &= P_{fA} * P_{fB} \\
p_{10} &= 1 - (p_{11} + p_{12} + p_{13}) = 1 - (P_{fA'} + P_{fB}) \\
p_{11} &= P_{fA'} - (P_{fB} * P_{fA'} * P_{fB} / (P_{fA'} + P_{fB})) \\
p_{12} &= P_{fB} - (P_{fA'} * P_{fA'} * P_{fB} / (P_{fA'} + P_{fB})) \\
p_{13} &= P_{fA'} * P_{fB} \\
p_{20} &= 1 - (p_{21} + p_{22} + p_{23}) = 1 - (P_{fA} + P_{fB'}) \\
p_{21} &= P_{fA} - (P_{fB'} * P_{fA} * P_{fB'} / (P_{fA} + P_{fB'})) \\
p_{22} &= P_{fB'} - (P_{fA} * P_{fA} * P_{fB'} / (P_{fA} + P_{fB'})) \\
p_{23} &= P_{fA} * P_{fB'} \\
p_{30} &= 1 - (p_{31} + p_{32} + p_{33}) = 1 - (P_{fA'} + P_{fB'}) \\
p_{31} &= P_{fA'} - (P_{fB'} * P_{fA'} * P_{fB'} / (P_{fA'} + P_{fB'})) \\
p_{32} &= P_{fB'} - (P_{fA'} * P_{fA'} * P_{fB'} / (P_{fA'} + P_{fB'})) \\
p_{33} &= P_{fA'} * P_{fB'}
\end{aligned} \tag{9}$$

To calculate p_{ij} for our system, we need given failure probabilities for both single WLAN's which will in the following be evaluated by experiment.

5. Measurement Setup

To obtain experimental performance data, we built a measurement system (Figure 7) with an IXIA network load generator [17], which allows precise traffic measurements.

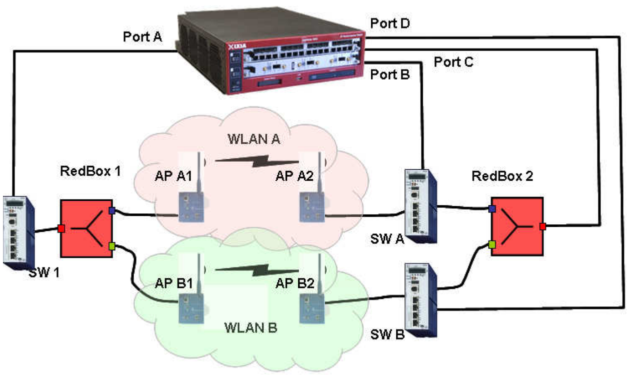

Figure 7. Measurement Setup

Nominal maximum line rate for the Ethernet parts of the system is 100 MBit/s. The setup was located in the Hirschmann R&D department, in an obstructed line-of-sight (LOS) distance between the APs of around 12 meters. It is basically the same setup as in [3], except that now all four WLAN devices are of type BAT300 and configured for 802.11n. WLAN A was placed on channel 40, WLAN B on channel 48. As shown in Figure 8, channel 48 is also used by other WLAN systems.

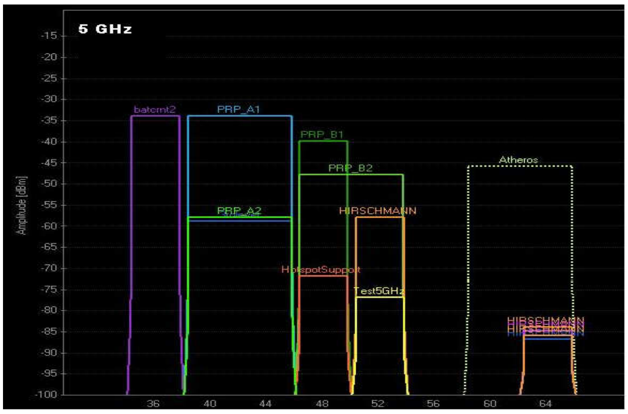

Figure 8. WLAN occupation

The traffic for the reliability and performance measurements was generated as described in Algorithm 1. The measurement duration for each combination of cycle time and packet size was 1 hour, whereas the cycle time is defined as the packet transmission interval time, consisting of the packet plus the gap to the next packet.

```
Packet_size = {64,128,512,1024,1280}        // in bytes
Cycle_time = {5,10}                          // in milliseconds
for each Packet_size do
    for each Cycle_time do
        for a duration of 1 hour do
            // send_multicast_packet(source_port)
            send_multicast_packet(A)
        end
    end
end
```

Algorithm 1. Fixed Line Rate Traffic

6. Measurement Results

6.1. Latency and Jitter

As value for minimum latency the time for the packet with the lowest delay within the same measurement period is taken. The single WLAN channels performed always better in comparison to the overall channel. This is due to the additional PRP boards, which introduce a penalty delay in the communication system.

For higher packet sizes, the difference increases because of higher process time for larger packets in the PRP boards (Figure 9).

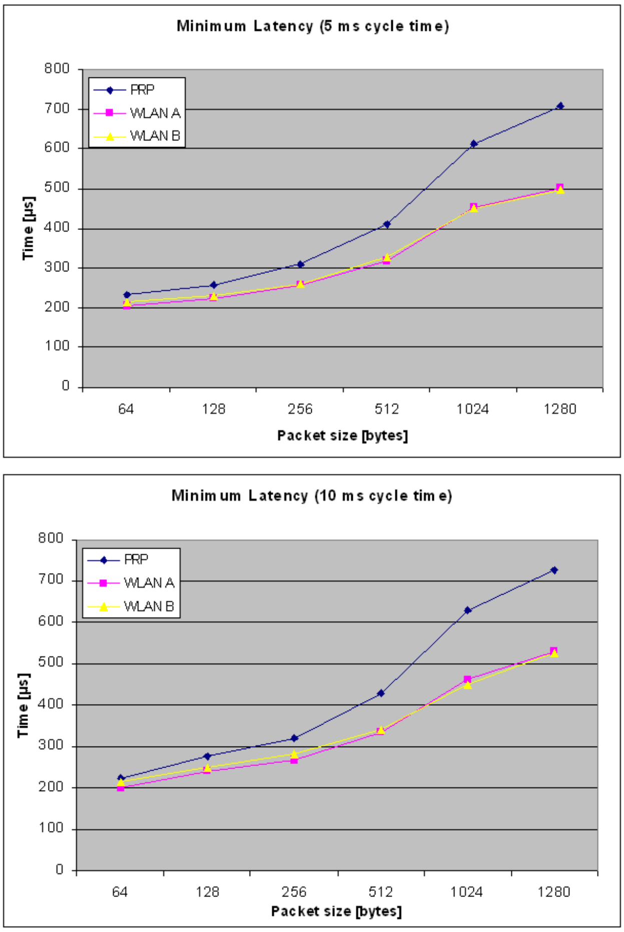

Figure 9. Min. Latency vs. Packet Size

As value for the maximum latency (Figure 10) the time for the packet with the highest delay within the same measurement period is taken (lost packets are not considered). In case the highest delays for both single WLAN channels won't happen at the same time instance, the parallel redundant system always get a better performance on the overall channel, since the faster of the two channels wins. This property is responsible for the performance gain of the presented approach.

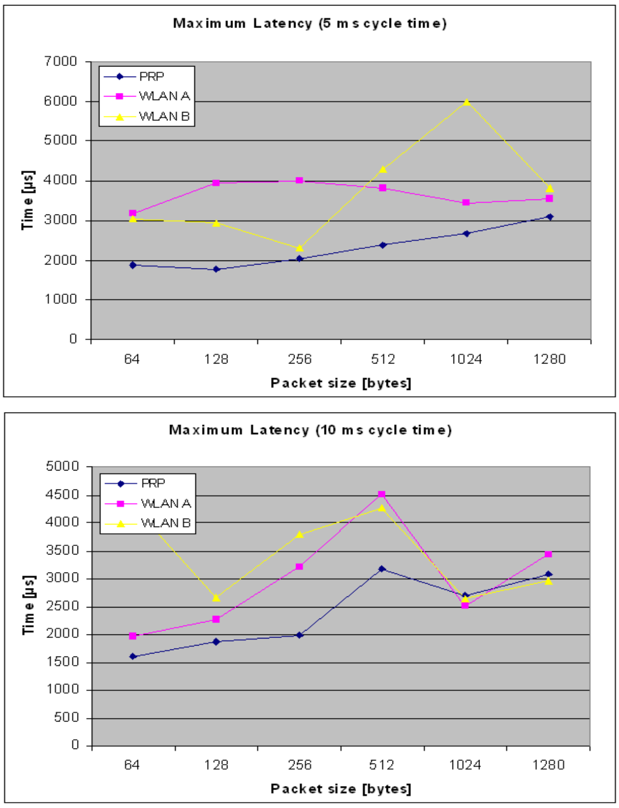

Figure 10. Max. Latency vs. Packet Size

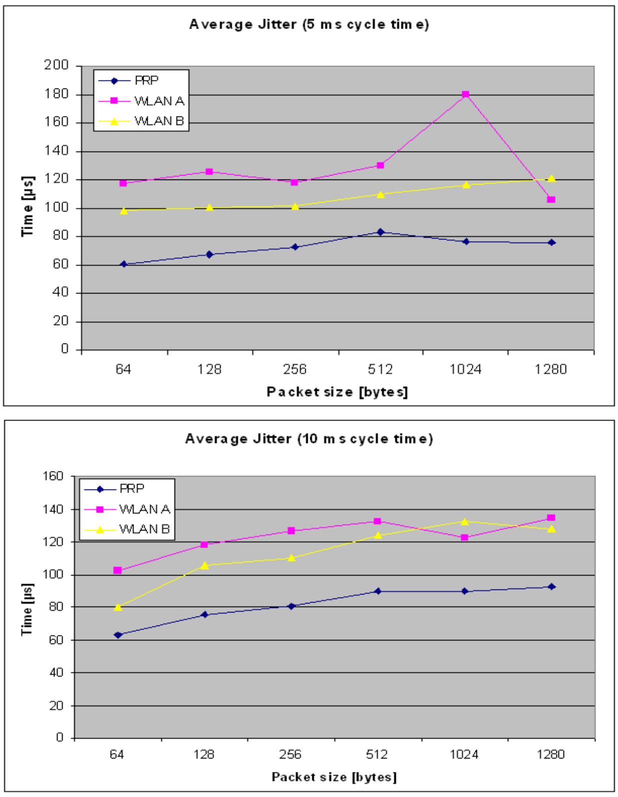

Figure 11. Jitter vs. Packet Size

The average deviation of the mean latency value (jitter) points out the main advantage of the PRP mechanism, as it always takes the faster arriving packet of both single WLAN. The jitter improvement factor J_{IF} for the overall system is stable above 1.4, thus according to equation 5, we yield an improvement of at least 40% for every measured traffic pattern. The peak for WLAN A at 1024 bytes indicates a temporary occupancy of the used channel. This had no effect on the overall PRP channel.

6.2. Packet Loss

In this measurement, we wanted to determine the throughput boundary where the system will start to show packet losses on the overall channel and the achieved improvement of throughput performance in the range of zero packet loss. To achieve this, a sweep over the transmission line rate was performed. For each packet size, measurements were taken for duration of one hour and the mean values calculated (Figure 12).

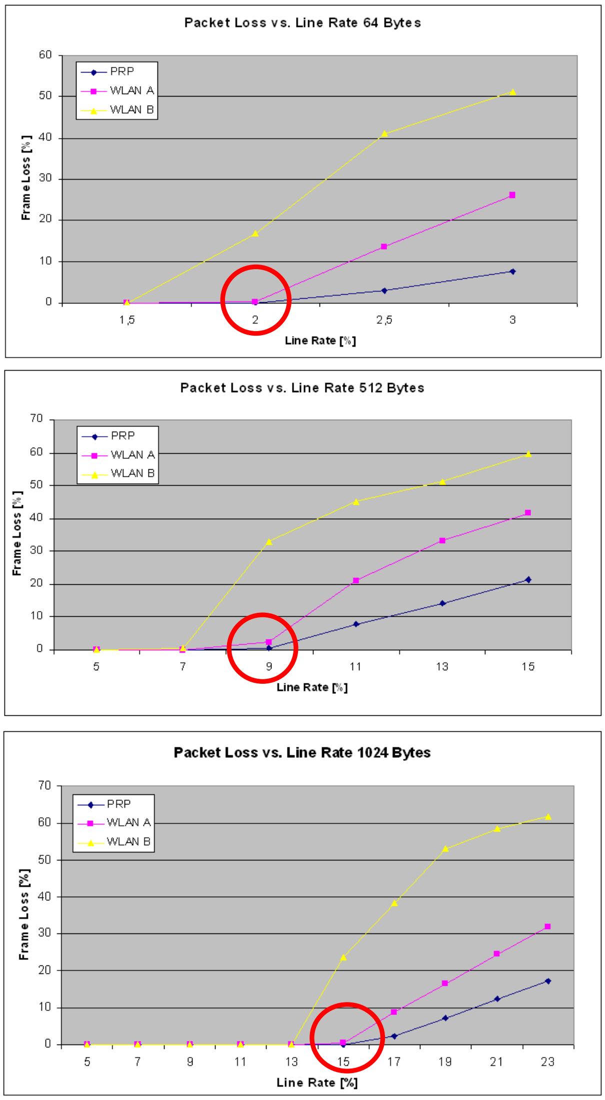

Figure 12. Packet Loss vs. Line Rate

The poorer performance of WLAN B compared to WLAN A lies in the fact that the channel of WLAN B was also utilized by another WLAN system. We observed that with increasing line rate the packet loss rate also increases. For every packet size there is a certain performance boundary where the overall channel is not longer able to compensate the high error rate of the single WLAN channels (circles in Figure 12). For 64 bytes the limit is at about 2%, for 512 bytes it increases to 7% and for 1024 the limit is at 13%. This might be due to the relatively large 802.11 overhead for small packets and the number of transmissions which decrease with larger packet size for the equal line rate. We can see from this measurement that the parallel redundant system yields only a minimal throughput gain within the range of high reliability, thus where the overall packet loss still remains zero (Figure 12). Beyond that limit, the overall channel yields up to 20% improvement in terms of less packet losses than the better performing single channel.

6.3. Reliability

For the fixed line rate measurements (Algorithm 1), the overall channel was always free of failures, while both single WLAN channels responded failures with a quite stable failure rate around 0.02 % (Figure 13).

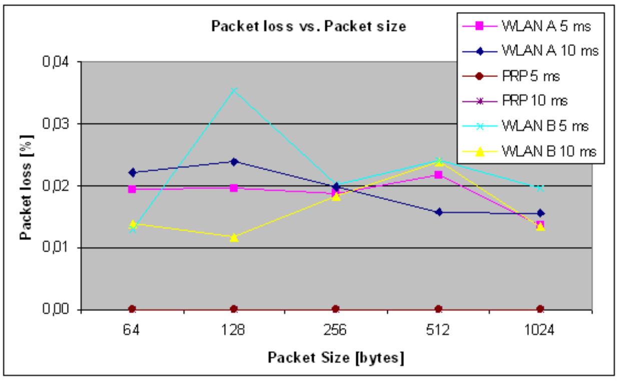

Figure 13. Packet Loss vs. Packet Size

This shows a perfect availability of the overall channel for the given settings and traffic (Algorithm 1). In contrast, the single WLAN channels showed high error rates in every measurement and are therefore not suitable for high availability requirements.

7. Numerical Simulation Analysis

To prove the applicability of the previously developed theoretical Markov model, measured failure probabilities of both single WLAN channels must be taken to simulate the failure probability of the overall channel. These simulation results have then to be compared with the measurements of the overall channel. Since the initial fixed line rate measurements (Algorithm 1) could not show errors on the overall channel, a further measurement campaign was conducted. To force errors on the overall channel, the transmission duration was increased to 24 hours (Algorithm 2).

```
Packet_size = {64,128,512,1024,1280}          // in bytes
Cycle_time = {5,10,15}                        // in milliseconds
for each Packet_size do
   for each Cycle_time do
      for a duration of 24 hours do
            // send_multicast_packet(source_port)
            send_multicast_packet(A)
      end
   end
end
```

Algorithm 2. Multiple Fixed Line Rate Traffic

In our measurements we analyzed the behaviour of the WLAN channels after a failure occurred. We observed an increase of up to 200 times for the failure probability $P_{f'}$, compared to P_f within the range of P_f = 0.05…0.01 %, which shows the error burst behavior of the WLAN technology. For increasing failure rates the factor decreases and converges against 1 for high failure probabilities. We choose the average value of 60 for numerical analysis of the Markov model with the given failure probabilities, yielding:

$$P_{fA'} = 60 * P_{fA} \quad (10)$$

$$P_{fB'} = 60 * P_{fB} \quad (11)$$

For channel modelling of other environments with different failure probabilities this factor has to be investigated and set accordingly.

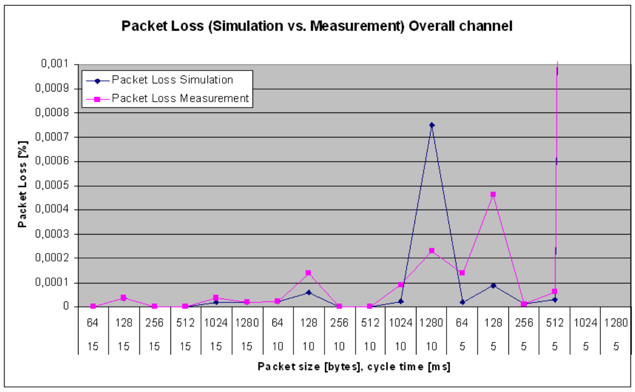

Figure 14. Simulation vs. Measurement

Numerical simulation was carried out with a simple self-written C program that utilized a pseudo-random number generator to feed the state machine transitions. The comparison between this numerical simulation and previous measurements showed similar results. The area of interest for our numerical simulation is indicated by the circles in figure 12, which are the packet loss boundaries for the overall PRP channel. Both measurement and numerical analysis indicate the same performance boundary starting at 1024 bytes/5ms where, for higher throughputs, the failure rates dramatically increase

(Figure 14). Our numerical simulation therefore works quite accurate for the given setup.

It must also be noted that we defined a Markov model with full transition matrix, which can likely be simplified by elimination of irrelevant transitions without significantly affecting the results.

8. Conclusion and Outlook

We showed with measurements on the Ethernet packet level that the parallel redundant WLAN system with PRP as splitter and selection combiner can provide a very high stochastic reliability under certain constraints. According to our findings, the most important point is to keep the throughput under the limit where the overall channel will with a high probability remain error free for the given environment. Our measurements have shown that there exists a relatively sharp boundary that depends on the line rate in conjunction with the packet size. Since both are application dependent, this boundary has to be carefully investigated in the planning phase for industrial applications. We showed that the numerical analysis based on a Markov model allowed the estimation of this performance boundary with a very good correlation to the measurements.

A suitable planning method and tool for this type of parallel redundant WLAN should therefore be developed, which remains a future work to be done. For this planning tool, the mentioned Markov simulation may be utilized, possibly with a more simplified model compared to the one presented in this paper.

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