Simulation of Parallel Redundant WLAN with OPNET

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Abstract

Applying multiple redundant and diverse communication channels is an established method to achieve an improved overall communication channel. When applied for packet-based data transmission over channels with strongly nondeterministic behaviour due to environmental influence, such as Wireless Communications, timing performance can be greatly improved by this approach.

The central element in such a system is the so called "Combiner" on the receiving side. In this work, a new specific type named "Timing Combiner" is described. The Parallel Redundancy Protocol (PRP) according to IEC 62439-3 realizes such a Timing Combiner on the Ethernet level.

In this work, an OPNET simulation model is created and analysed for its performance characteristics. Also a quantitative analysis of the effect of different interference models in an industrial environment is presented.

1. Introduction

Data communication technologies like WLAN according to IEEE 802.11 [1] are promising for the use in industrial applications. It easily interoperates with IEEE 802.3 (Ethernet) [2] LAN technology, which is already widely used for industrial networks. On the other side, it uses a shared medium with a behavior that is known to be error-prone and showing time-variable and non-deterministic error characteristics. This labels WLAN usually not very well suited for industrial applications with tight reliability requirements, such as guaranteed maximum latency times for packet transmission.

Redundancy techniques based on diverse communication channels (see Fig. 1) are an established countermeasure to improve performance characteristics of wireless communication systems on a stochastic basis [3, 4]. This is a thoroughly researched subject and Brennan's classical 1959 paper [3] describes the basic forms of diversity for wireless communication as well as the basic diversity combining approaches. Brennan's terminology has become accepted standard in this field. Although in his days, the focus was on the transmission of instantaneous analogue signals in terms of the signal-to-noise-ratio (SNR), the principles can of course also be adopted for digital data communication. For longer signal sequences, such as for example Ethernet packets, specific performance characteristics regarding diversity gain can be observed, that are going to be more thoroughly researched in this ongoing work.

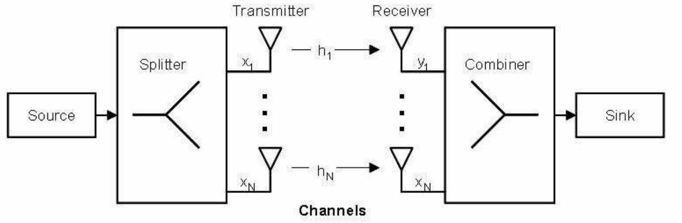

Figure 1. Wireless Diversity System

IEC 62439-3 [5] describes a "Redundancy Box" (RedBox) for the "Parallel Redundancy Protocol" (PRP) that can be at the receiving side modeled as a post-detection **selection combiner** according to the classification scheme in [3]. Out of the two branches the first arriving Ethernet packet is selected and further processed. The second packet -if arriving- is discarded. Thus we have named this type of combiner a "**timing combiner**", since a significant timing improvement is gained, as has been demonstrated in [6] and [7].

Since long term measurements as performed in [6] and [7] to gather a sufficient basic population for stochastic analysis is resource demanding, it would be helpful to have a simulation tool to analyze the performance behavior of such a system. It is therefore the purpose of this work to qualitatively verify the previously measured observations by simulation with OPNET [8].

The paper is structured as follows: In section 2, some background of wireless diversity systems is presented, section 3 shortly describes the parallel redundancy protocol and its combiner property. Section 4 develops a channel model on OPNET Network Modeler and presents the simulation results. Finally, section 5 concludes on the findings and the possible further work.

2. Diversity System Taxonomy

Brennan's nomenclature [3] has become accepted standard in the field of wireless diversity. Although in his days, the focus was on the transmission of analogue signals in terms of the *signal-to-noise-ratio* (SNR), the principles can of course also be adopted for digital data communication with focus on the behavior of longer signal sequences. The important terms are shortly explained below.

Space diversity: The same signal is transmitted in parallel over several different propagation paths.

Time diversity: The same signal is transmitted more than once, but at different time instants.

Frequency diversity: The same signal is transmitted in parallel over several frequency channels or spread over a wide frequency spectrum.

All these diversity techniques have the goal to bring at least one of the signal copies in the best possible quality over one of the redundant channels to the receiving side. Brennan [3] has also classified the basic diversity combining methods and grouped them as follows:

Gain Combining: The instantaneously received signals of all branches are added. This method requires the received signals in the same phase. Gain combining increases the signal-to-noise-ratio (SNR) of the overall signal at the receiver. It is commonly distinguished between "Maximal-Ratio Combiner" and "Equal-Gain Combiner".

Scanning (Switching) Combining: The receiver switches to another branch when the signal of the currently selected branch drops below a predefined threshold.

Selection Combining: Of the instantaneously received signals of all branches only the strongest signal is selected, the other branches are ignored. This is more efficient than scanning combining.

In [7], the following term for the new combining technique was introduced:

Timing Combining: Adheres to the principle of selection combining, but instead of the strongest, the fastest signal of all branches is selected, the other signals are ignored. This approach proves especially effective for longer signal sequences, such as data packets, that are transmitted in smaller sub-portions with recovery protocols over the wireless links and then reassembled on the receiving side (see Fig. 3).

3. Parallel Redundancy Protocol

The "Parallel Redundancy Protocol" (PRP) according to IEC 62439-3 [5] was developed to achieve seamless redundancy for highest availability of Ethernet networks. In [6] and [7] it was on an experimental basis utilized 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 (Fig. 2). In [7], a more detailed measurement to gain a deeper insight into the performance behavior of such a parallel redundant WLAN system was conducted with focus on Ethernet packet transmission behavior and not safety application protocol behavior as in [6]. Both cases demonstrated that the PRP-WLAN system achieved a significant improvement not only in packet loss but especially in timing behavior compared to a single WLAN channel. This property of improving timing behavior allows the application of such a system for industrial protocols with higher requirements on synchronicity.

3.1. Redundancy Box as Timing Combiner

The PRP RedBox can be at the receiving side modeled as a selection combiner, where out of the two branches the "better" signal is selected, in this case the first -or faster- arriving Ethernet packet, which is then immediately further processed. The second packet -if arriving within the PRP timing window- is discarded. This can be described as follows:

$$\mathrm{ETH}\quad X = \begin{cases} \mathrm{ETH}\quad A & \text{if } (t_A < t_B) \\ \mathrm{ETH}\quad B & \text{otherwise} \end{cases} \tag{1}$$

t_A and t_B reflect the arrival times of a duplicated packet at the respective ETH interface. Thus we call this a "Timing Combiner".

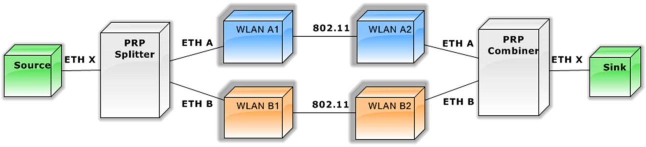

Figure 2. PRP-WLAN Architecture

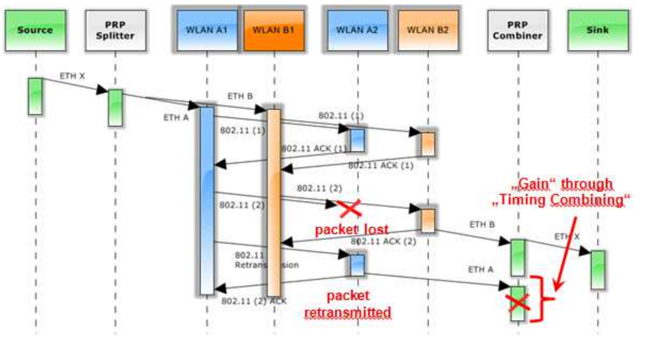

Figure 3. PRP-WLAN Timing Scenario

A major influencing factor in the PRP-WLAN system is that Ethernet packets are a longer sequence of signal instants, which are often sequenced into smaller pieces to be transmitted over 802.11 and reassembled on the receiving side. This is depicted in the sequence chart in Fig. 3, where the impact on the timing behavior is highlighted.

4. OPNET Model

In this section, the aforementioned PRP-WLAN channel network model will be developed on OPNET Network Modeler. An analysis of the model will be conducted in both a noise-free and a noisy environment, with different noise models. Since the proposed PRP-WLAN system utilizes Wi-Fi operating in the Industrial, Scientific and Medical (ISM) band, this work will be focused on studying the effect of different ISM band interferers on the system. In [9], various ISM band interference models with varying degrees of strength are presented. They will be used to formally quantify the effect of interference on the proposed PRP-WLAN system.

4.1. Noise Free Parallel Redundancy Protocol Model

The first step was to build a model based for the PRP-WLAN system presented in [6,7], using OPNET Modeler (see Fig. 4). The first node, Sensor, is connected to a switch, which is linked to two access points (APs) working on two different non-interfering channels 1 and 9 using 802.11g, modeling a PRP system. For our purposes, IEEE 802.11g provides adequate data transfer rates suitable for many industrial applications. In all OPNET models, the PRP RedBox is simulated by the switch. It performs packet duplication, one for each channel, with the addition of a byte trailer and a sequence ID to each packet. On the receiving side it analyses the sequence ID, strips the trailer from the packet and discards any already received duplicate. This node is sending identical data to a similar infrastructure on both channels (to the Actuator).

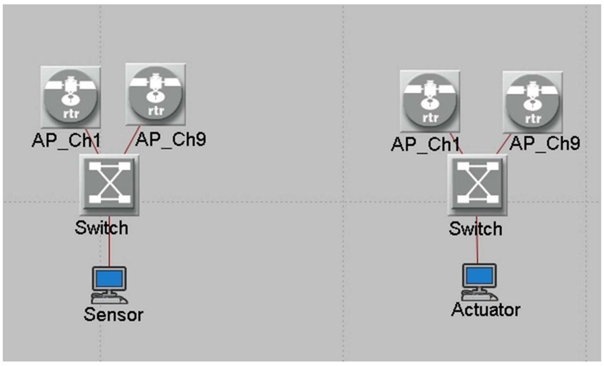

Figure 4. OPNET Model without Added Noise

Simulation system parameters are shown in Table I.

Table I. Model Specifications

Parameters	Value
Sampling Period	5ms
Transmission Power	0.03Watts
Transmission Data Rate	24Mbps
Distance between Nodes	12m
Distance between Wireless (AP) Interfaces	30cm
System Transport Layer Protocol	UDP

Figure 5 indicates successful communication on the packet level for channels 1 and 9. The independent variable of the plots is the simulation time while the dependent variable of the plots represents the number of bytes sent/received. The data sent by the Sensor and received by the Actuator, respectively on channel 1 and 9, are superimposed in a single plot, indicating a successful communication.

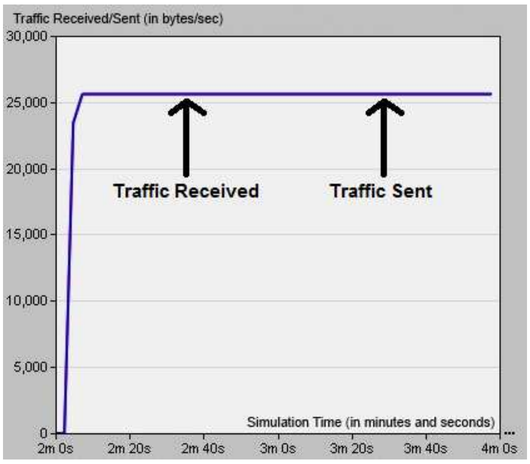

Figure 5. Traffic Received/Sent on Channel 1 & 9

4.2. Medium Congestion With Parallel Redundancy Protocol

The main goal of the OPNET simulations presented in this paper is to verify the superiority of the PRP-WLAN system particularly in noisy environments. To achieve this, three network criteria are measured and the single channel systems are compared to the PRP channel model. The three network performance criteria are latency, jitter and packet loss.

Latency: It is the average end-to-end delay of all the packets sent during simulation.

For each scenario, 33 simulation runs were conducted and the end-to-end delay of each single run was measured regarding channel 1 only, channel 9 only and the PRP system. Then the average end-to-end delay of the three proposed systems was calculated for each of the 33 runs.

Jitter: It is the standard deviation of the end-to-end delay of all the packets sent during simulation.

The aforementioned technique being utilized for the sake of calculating the maximum latency was used again for the calculation of jitter using standard deviation instead of the straight average.

Packet Loss: For a given sampling period, if a packet gets delayed for a period greater than that of the sampling period, then this packet is considered lost (since over-delay can cause a failure of the real-time system under study).

In order to test the packet loss in the presented system, the most delayed packet is observed, and its delay is compared to80% of the sampling rate (80%×5ms = 4ms), to provide a margin of possible error [9]. A similar approach to that applied for the calculation of jitter and latency was conducted for the computation of the maximum delayed packet. A third statistical too1 was utilized, which was the maximum of all values. 14 cases of noise file size are tested. The noise file size is swept according to the following equation (2).

$$\text{Noise } File\ Size = 2^n \text{ for } n = 1:14 \qquad (2)$$

All the results, presented in this work, are based on a 95% confidence analysis.

4.2.1. Application Noise on Channel 1 only

The first proposed noise model consists of two laptops placed in the middle of the workcell described in the previous section utilizing File Transfer Protocol (FTP). References [9-11] demonstrate the use of different noise models. In some of these noise models, the degree of interference is quantified for the maximum tolerable value by sweeping the transmitted FTP file size of the interfering nodes. For the model presented in this section, the two laptops are also exchanging files using FTP via an access point operating and consequently interfering on channel 1. Thus, for this section, the FTP noise file size is used as the main noise quantification metric. Table II shows the FTP traffic parameters used to model noise on channel 1. Figure 6 shows a schematic of the proposed noise model.

Table II. Noise Traffic Specifications

Parameters	Value
Inter-Request Time	0.5s
Transmission Power	0.1Watts
Transmission Data Rate	54Mbps
Distance between Nodes	12m
Noise Transport Layer Protocol	TCP

Primarily, the PRP system has led to a better performance regarding maximum latency. Figure 7 shows that beyond a noise file size of 2KB, channel 1's performance degrades compared to channel 9 with regards to latency. This is an expected result, since the PRP model accepts the packet which reaches the receiver at first, so its overall latency is anticipated to be better than that of a system using a single channel. Note that the latency of the PRP system is the average of the minimum latencies achieved over both channels. Also using channel 1 or channel 9 alone yields identical results at first and then the latency values of channel 1 start to diverge, since at low noise file sizes, the noisy nodes have a minimal effect on medium contention. However, beyond the 2KB value, the nodes start to have a strong impact. It is also noticed that the PRP system's latency curve can be modeled as a straight line. This is due to the fact that the latency is approximately constant with different values of noise. This is because the packets arriving first at the receiver would have similar latency values equal to that experienced on the other channel because the interference is only affecting one of the two channels. Hence, the PRP system exhibits an improvement of at least 28.7% over the single channel system

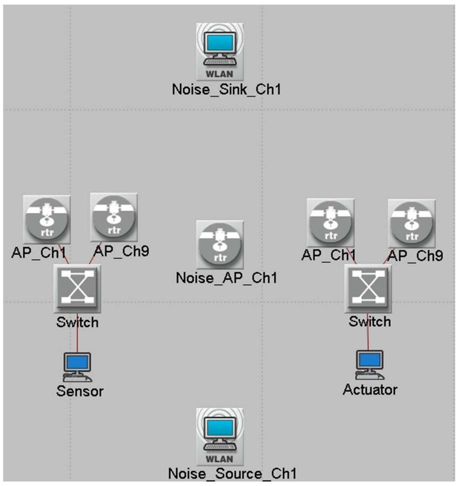

Figure 6. OPNET Model with Single Channel FTP Noise

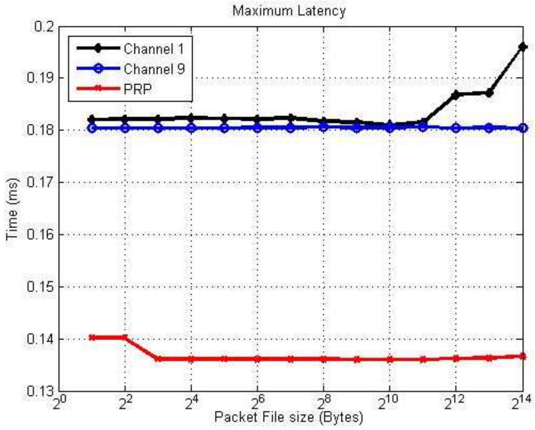

Figure 7. Maximum Latency with FTP Noise on Channel 1 only

Moreover, the results also show that the PRP system yields better performance regarding jitter. Figure 8 shows that using a single channel yields higher jitter than using the PRP system as anticipated. The PRP system always receives the minimum delayed packet, which will have values deviating at smaller ranges than that of the end to end delay of the single channel system. Hence the PRP system is more immune to the jitter issue than a single channel system. Also since the noisy nodes are sending files via an access point that is working on channel 1, at high noise file sizes beyond 2KB, channel 1 starts to individually yield higher jitter than that of channel 9. This is because even at stronger interference, which occurs by having larger noise file size, the delay of faster arriving packets will still fluctuate on very small range, since only one of the two mediums is congested. Hence the PRP system shows an enhancement of at least 287.11% over the single channel system

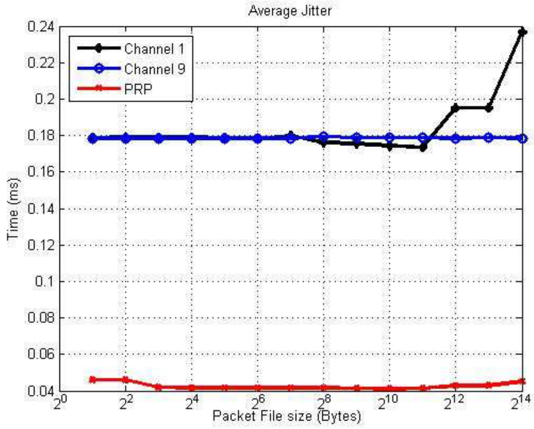

Figure 8. Average Jitter with FTP Noise on Channel 1 only

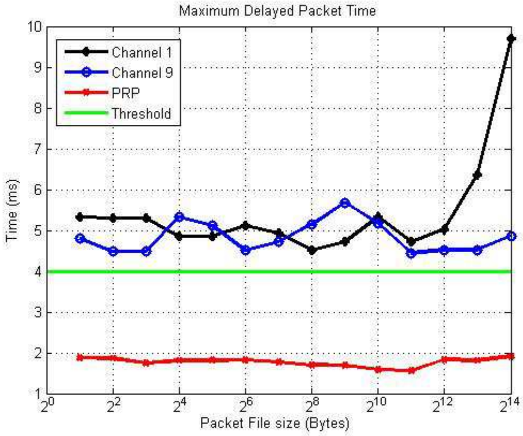

Figure 9. Maximum Delayed Packet with FTP Noise on Channel 1 only

Finally, regarding packet loss, Fig. 9 shows that using single channel systems will certainly suffer from packet loss even at very low noise file sizes. This implies that the single channel system cannot tolerate medium interference on channel 1. The packet loss is calculated by comparing the delay value of the most deferred one to 80% of the sampling period as previously explained. However it is clear that the PRP system can tolerate different noise file sizes and will never encounter packet loss, verifying the results from [7] but with added quantification of noise in terms of file sizes. This is because the noise is only on one channel; so, at very high noise file size; the faster packet will most probably be the one which was sent on channel that is not suffering from external inference, which in this case would be channel 9. This shows that the PRP system is more noise tolerant than the single channel systems. In Fig. 9, the 4ms line represents the threshold over which packets having higher delays, will eventually suffer from packet loss.

It is important to note that all delays presented in this work include all propagation, encapsulation/decapsulation, queuing and processing delays and that the system under study does not experience any dropped or over-delayed packets.

4.2.2. Application Noise on Channel 9 only

In this model, the noise access point is operating on channel 9, causing medium congestion on this channel. This simulation was performed to verify the results of the first experiment. It yields the same results as the first experiment with the results of channel 1 swapped with those of channel 9 as single channel systems. This is why the noise in this case is subjected on channel 9 instead of channel 1.

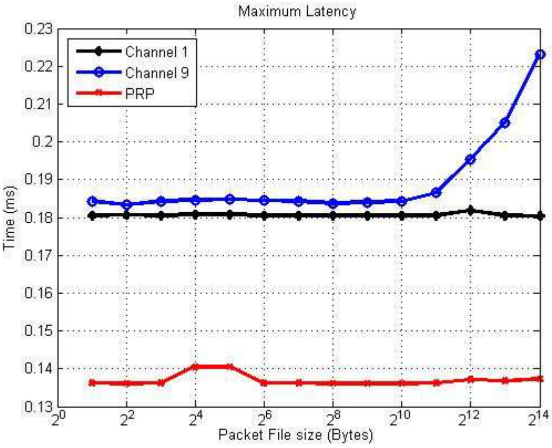

Figure 10. Maximum Latency with FTP Noise on Channel 9 only

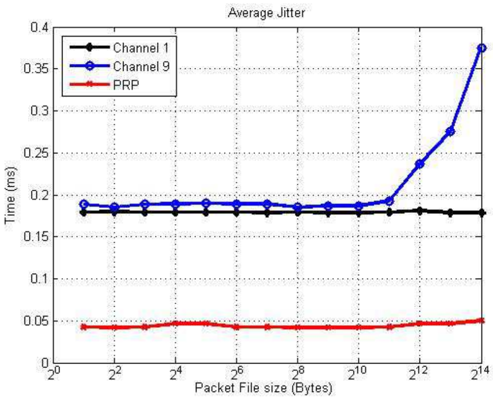

Figure 11. Average Jitter with FTP Noise on Channel 9 only

The PRP remains a system which is characterized by lower latency and jitter compared to single channel system, with no packet loss. As expected, the presented results are similar due to the fact that channel 1 and 9 are two non-interfering channels in 802.11g Wi-Fi. Figures 10 to 12 show the comparison between three systems regarding latency, jitter and maximum packet end to end delay respectively. The latter figure illustrates packet loss, if any.

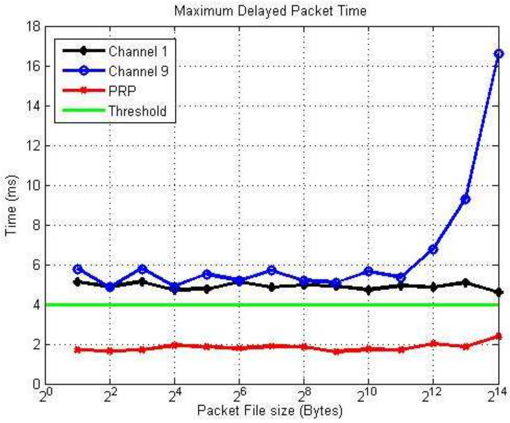

Figure 12. Maximum Delayed Packet with FTP Noise on Channel 9 only

4.2.3. Application Noise on Channel 1 and Channel 9

This scenario has the same proposed workcell, with the presence of 2 pairs of laptops in its middle. The first pair is exchanging files using FTP via an access point operating at channel 1. At the same time the other two workstations are transferring files through another access point which is functioning at channel 9. Hence this proposed model is anticipated to suffer from a noisier environment as noise is applied on both channel 1 and 9 simultaneously (Figure 13).

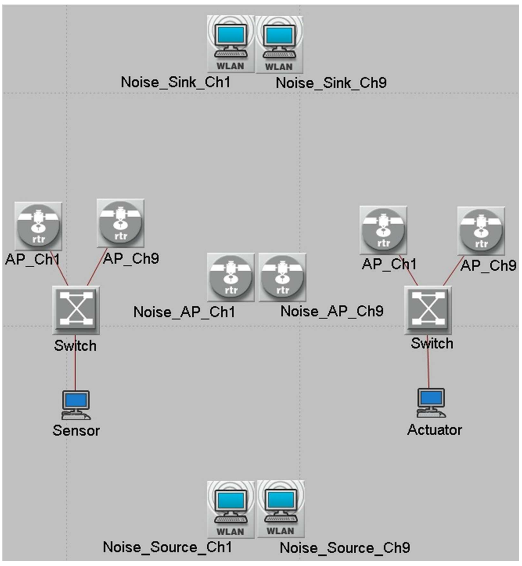

Figure 13. OPNET Model with Dual Channel FTP Noise

First of all the PRP system shows that it has lower latency values compared to using a single channel of either 1 or 9. As expected, both channels 1 and 9, as single channel systems, exhibit the same performance. The PRP system did not preserve the straight line trend of the two preceding noisy settings. This is because at relatively high noise files (2KB), the latency values start to increase over both individual channels, however it maintains its advantage over single channel systems, which is enhanced latency immunity. This increase is due to the fact that, in this case, the entire medium is congested, in contrary to the prior two cases where only one of the two channels was congested. Hence, at noise file sizes of 2KB and higher the effect of noise would be the same on both channels, so that the first arriving packet will take longer time than usual.

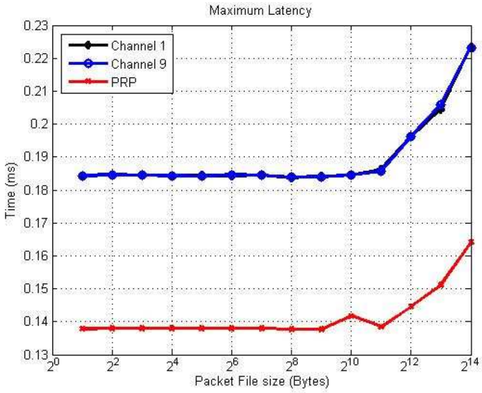

Figure 14. Maximum Latency with FTP Noise on Channels 1 and 9

Figure 14 shows the comparison between the performance of the PRP system and the single channel system (either channel 1 or 9) regarding latency. Hence the PRP system shows an enhancement of at least 30.15% over the single channel system.

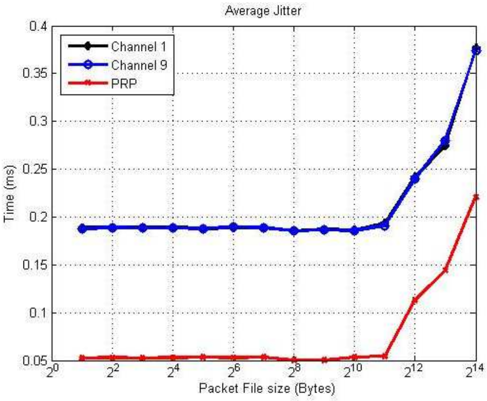

Figure 15. Average Jitter with FTP Noise on Channels 1 and 9

Moreover, the PRP shows improvement in jitter compared to the single channel structure. As anticipated, using either channel 1 or 9 will have precisely identical results. Similar to the case of latency, the PRP system no longer exhibits constant values, since each of the channels 1 and 9 are subjected to noise, hence the entire medium is congested. Thus the packets would start to arrive at the receiver with bigger deviations, which leads to larger jitter. The breakout file size is exactly the same as in the latency case, which is around 2KB. Figure 15 shows the previously clarified outcome. Hence the PRP system shows an enhancement of at least 69.5% over the single channel system.

Finally, it is verified that the PRP system has improved performance, concerning immunity to packet loss compared to the single wireless interface scheme. However, in contrary to the preceding two noise models, the PRP system can only tolerate file sizes, up to a certain limit, around 4KB, beyond which the network would start encountering packet loss. This is predictable due to the fact that now the medium is fully congested, thus at high noise file sizes, the delay of the faster arriving packets to the receiver would eventually exceed the threshold value, 4ms, causing packet loss (Contrary to the two previous noise schemes, in which the medium was only partially congested). This shows that using the PRP model induces an increase in the maximum tolerable noise file size compared to the single channel system. Figure 16 shows the clarification of the described outcomes regarding packet loss.

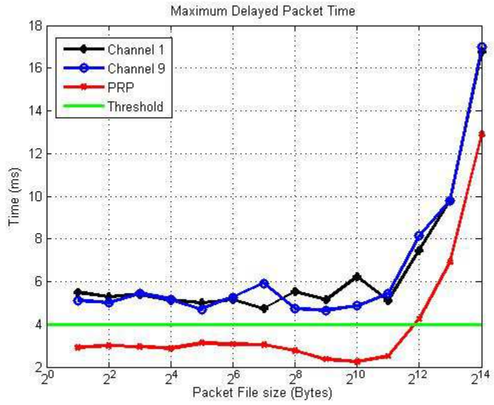

Figure 16. Maximum Delayed Packet with FTP Noise on Channels 1 and 9

4.3. Single Band Jammer

Jammers represent intended interference on communication networks. OPNET provides 3 types of jammers which are single band jammers, pulsed jammers and frequency swept jammers [9]. The single band jammer targets a certain frequency band continuously. The pulsed jammer transmits on a certain frequency band for a certain pulsating time. Finally the frequency swept jammer transmits uninterruptedly over a certain base frequency which changes at a certain specified rate. It was shown in [9] that the single band jammer model represents a worst case interference analysis. In this research, the single band jammer is therefore utilized as the interfering model to the workcell previously discussed. The frequency band of the jammer would be the whole 802.11g frequency band. The jammer is placed in the middle of workcell, where it would have the most powerful interference effect, to test the system under worst case.

Latency, jitter and packet loss are also used as indicators for the model. The jammer transmits different packet sizes along the same range of noise file sizes described in equation (2). Measurements of the three network factors are calculated on this specified range.

It is anticipated that the jammer would have a more drastic effect compared to the three different congestion models being tackled in this paper. This is because the jammers are interferers which affect the physical layer of the network as opposed to the aforementioned medium congestion noise models. Hence, the jammers' impact on the network performance is much more tangible.

Figure 17 manifests the fact that the PRP design still preserves its superiority compared to the single channel as previously mentioned regarding latency. It shows an enhancement of at least 10% over the single channel system.

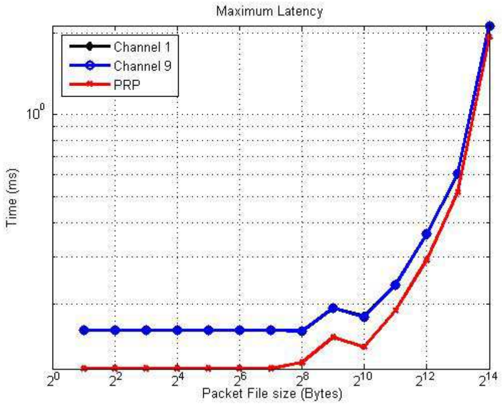

Figure 17. Maximum Latency with Jammers as Interferers

Figure 18 shows the performance in the context of jitter. The PRP system shows an enhancement of at least 5% over the single channel system.

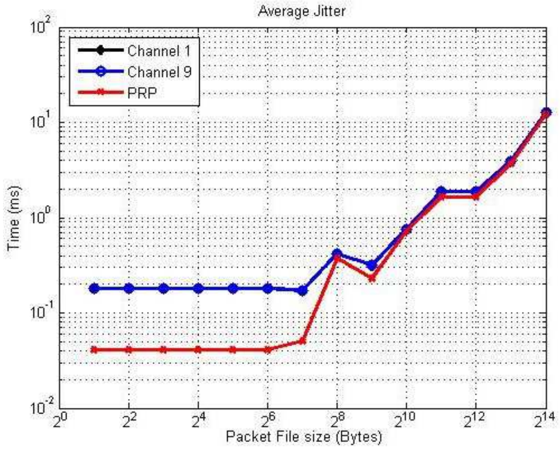

Figure 18. Average Jitter with Jammers as Interferers

Similar to the latency, jammers also impacted the medium more harshly than that in the presence of the FTP laptops and leads to a larger deviation in the delays, thus higher jitter.

Finally the PRP system shows some tolerance to jammers regarding packet loss, while the single channel would encounter packet loss regardless of the packet size being sent by the jammer. Figure 19 shows that the PRP system can tolerate packet sizes that can reach up to 512Bytes. The tolerable packet size is not as big as that in case of FTP application due to the fact that jammer's have a higher interference impact, which causes the fast arriving packet at the receiver in the PRP system to exceed the 4ms threshold at lower packet size.

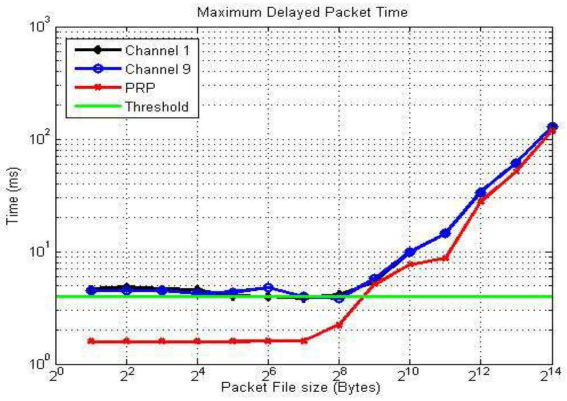

Figure 19. Maximum Delayed Packet with Jammers as Interferers

5. Conclusion

The PRP-WLAN system was simulated using different noise schemes and the effect quantified on the single channels as well as the PRP system. The noise schemes were simulated with two laptops exchanging files using FTP via access points operating on channel 1 alone, channel 9 alone or on both channels. Then the performance of the PRP was compared to single channel structure in the presence of jammers. All results are subjected to 95% confidence analysis.

It was shown that the PRP system has a better performance than a single channel in the context of latency and jitter. When only one channel is subjected to interference, the PRP system will not suffer from packet loss at all. Packet loss is expected to occur when interference is on both channel 1 and 9 simultaneously, however, the PRP will tolerate up to a certain FTP file size (4KB). When jammers are used to simulate worst case interference, packet loss will certainly occur for a single channel, whereas the PRP system will tolerate noise up to a FTP file size of 512Bytes. This implies that the single channel system is intolerable to any of the interference models investigated in this study. The results of the different types of interference indicate that the jammers are more damaging than medium congestion.

The simulation results strongly resemble the previously measured system behavior in [6] and [7] and prove that the OPNET model is suitable for a detailed analysis of the parallel redundant WLAN system. Note that the simulation results are only qualitatively comparable to those in [6] and [7], since differing parameters (such as the use of IEEE 802.11g vs. IEEE 802.11n in [7]) and different means of data generation and transmission had to be used in the simulation environment.

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