Simulative Comparison of Parallel Redundant Wireless Systems with OMNet++

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Abstract—**Parallel redundant point-to-point transmission utilizing a dual-radio wireless infrastructure has been identified as a powerful approach to improve the performance of wireless communication. This method can be applied for every existing wireless standard, but has not been deeply researched so far. To fill this gap, an OMNet++ simulation model for IEEE 802.11g (Wi-Fi) and IEEE 802.15.4 (ZigBee) is developed and some simulation scenarios performed to get a better understanding of the comparative performance characteristics of parallel redundant operation for these wireless standards.**

Keywords—Diversity, OMNet++, Parallel Redundancy, Wi-Fi, ZigBee

I. Introduction

The performance of a wireless communication standard in a, by nature, shared wireless medium is mainly influenced by its modulation and coding scheme plus the medium access control (MAC) layer mechanisms. Significant improvements can be achieved by applying diversity, which is basically the redundant transmission of information over stochastically uncorrelated channels [1]. Diversity measures on the physical (radio frequency) layer of the wireless transmission chain are often called pre-detection combining approaches. Additionally one can also utilize post-detection combining methods in the higher layers of the information processing chain of the communication system. A well-known example for this are MIMO technologies, which utilize spatial multiplexing by space-time coding and signal transmission over several antennas to achieve both coding gain and diversity gain. Implementations of the MIMO principle can be found in WiMAX, HSPA+, LTE and IEEE 802.11n.

Other post-detection diversity schemes utilize parallel redundancy in the space and frequency domain and are able to yield specific gains especially in packet transmission schemes [2]. A recently presented example is Parallel Redundant WLAN (PRP-WLAN, see Fig.1), which uses the Parallel Redundancy Protocol (PRP) according to IEC 62439-3 as splitter and combiner units on the Ethernet level and yields significant improvements [3, 4]. Such a parallel redundancy strategy could also be employed to improve other wireless systems, such as ZigBee or Bluetooth.

Previous work has been done to analyze the performance of a PRP-WLAN system under the effect of interference [5]. Results of this simulative analysis showed an improvement in the system's performance in general compared to a single channel system, with better results in latency and jitter, as well as higher tolerance to interference. This kind of research is still missing for other wireless standards such as ZigBee.

The paper is structured as follows: In section 2, the basics of Wi-Fi, ZigBee and PRP are shortly outlined and previous work is mentioned. Section 3 describes the OMNet++ [6] model and section 4 presents the simulation results, whereas section 5 compares the protocols based on the simulation results. Finally, section 6 concludes the study.

II. Technology Basics

The relationship between IEEE 802.15.4 and ZigBee [7] is similar to that between IEEE 802.11 and the Wi-Fi Alliance [8]. The expressions are often used synonymously.

A. IEEE 802.11 (Wi-Fi)

IEEE 802.11 is a series of standards which specify the physical layer and MAC for high-rate Wireless Local Area Networks (WLANs), operating in the 2.4GHz and 5GHz Industrial, Scientific and Medical (ISM) radio bands, IEEE 802.11 offers theoretical data rates up to 600Mbps. In both DCF and PCF mode, the physical medium is accessed through a "Carrier Sense Multiple Access with Collision Avoidance" (CSMA/CA) protocol, which is an unslotted transmission approach based on the listening of the medium before transmission and is leveraged by a random backoff algorithm.

On the MAC layer, a stop-and-wait automatic repeat request (ARQ) mechanism is used, where each successfully received frame is acknowledged by a confirmation message. If the sending device is unable to receive the confirmation message within a given time, it performs a number of this kind of timeout-based retransmissions until abortion. Whereas the CSMA/CA approach is adding a significant transmission latency offset due to the medium sensing phase, the ARQ mechanism is, in case of retransmissions, not able to achieve guaranteed packet delivery times and the synchronicity required for tight real-time processes. Both aspects form a major weakness in utilizing IEEE 802.11 for industrial-grade real-time applications in the presence of coexisting devices.

B. IEEE 802.15.4 (ZigBee)

IEEE 802.15.4 is a standard which specifies the physical layer and MAC for Low-Rate Wireless Personal Area Networks (LR-WPANs). It forms the basis for standards like ISA100.11a, WirelessHART, ZigBee and 6LoWPAN, each of which extends the standard by developing the upper layers not defined in IEEE 802.15.4 itself. ZigBee is therefore a specification for a suite of high level communication protocols making use of small, low-power digital radios. ZigBee can operate in the 2.4GHz ISM band in most jurisdictions worldwide or 868MHz in Europe and 915MHz in USA and Australia. Data transmission rates vary from 20Kbps in the 868MHz band to 250Kbps in the 2.4GHz band.

The ZigBee network layer natively supports, beside star topology networks, also tree and generic mesh topology networks by the use of so called ZigBee Routers. Every network must have one coordinator device, responsible for creation, control and basic maintenance of the communication relationships. For star network topologies, the coordinator must be the central node.

ZigBee protocols can support both non-beacon and beacon enabled networks. In non-beacon-enabled networks, an unslotted CSMA/CA channel access mechanism is used. In beacon-enabled networks, beacons are sent on a fixed timing schedule. For low latency real-time requirements, devices may also use Guaranteed Time Slots (GTS). CSMA is, by definition, not used in beacon-based ZigBee traffic and ACKs are transmitted within the beacons.

C. IEC 62439-3 (PRP)

In a Parallel Redundancy Protocol (PRP) system, every packet is sent by the source over at least two separate channels. The packet that is received first by the receiver is utilized and a later received duplicate is discarded. For the duplicate detection, each packet must contain suitable unambiguous identifiers. An IEEE 802.3 (Ethernet) based PRP mechanism for high availability networks has been standardized in IEC 62439-3, where the Ethernet MAC address and a sequence identifier is used for duplicate detection [9].

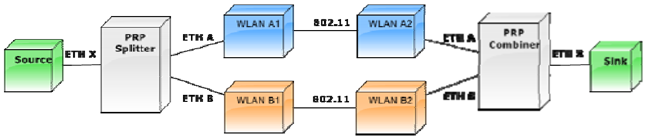

Fig. 1. PRP-WLAN system

This mechanism has been experimentally combined with WLAN-Devices in [3] and [4] to form a PRP-WLAN (Fig. 1), gaining significant performance improvements in terms of latency stability and packet loss.

III. Model Description

For both Wi-Fi and ZigBee systems, interference on a channel will result in retransmission until a successful transmission is achieved. This, in turn, causes delay in the packet delivery. In the PRP system, every packet is sent by the source over two non-interfering wireless channels. The packet that is received first by the respective destination is utilized and the duplicate is discarded. This mitigates the effect of delay when packet retransmission occurs on one of the two channels.

The models are built and simulated on OMNet++ [6]. The 802.11g model was simulated using the INET Framework [10], while ZigBee was modeled as 802.15.4 in non-beacon mode using the MiXiM Framework [11]. For each scenario, 33 seeds are run, and all simulation results are subjected to a 95% confidence analysis. The systems consist of two sensor nodes communicating over two non-interfering channels and are separated by a distance of 2 meters. Default bit-rate parameters were used for the 802.11g and 802.15.4 models; 54Mbps and 250Kbps respectively. Two different Wireless Network Control System (WNCS) applications were simulated, High-Load and Low-Load, to show the performance in different environments.

Fig. 2. OMNET++ Model for Wi-Fi

In the High-Load WNCS application, sensor nodes are using a sampling period of 40ms, while the Low-Load WNCS application sensor nodes are using a period of 1s. Sensor nodes are utilizing ‘UDPBasicApplication’ in Wi-Fi and ‘SensorApplLayer’ in Zigbee as their communication application. Other parameters like payload size, sensitivity, and signal attenuation threshold were kept constant in both protocols and applications while the sampling period of the interfering nodes was swept over. The values are as shown in Table I.

TABLE I. MODEL SPECIFICATIONS

Parameter	Value	
Sampling Rate	*High-Load WNCS*	*Low-Load WNCS*
	40ms	1s
Transmission Power	0.5mW	
Distance Between Nodes	2m	
Channel Sensitivity	-95dBm	
Signal Attenuation Threshold	-100dBm	
Payload Size	100Bytes	
System Transport Layer Protocol	UDP	

A. Interference Models

The interference model consists of two laptops, as in [5], placed in the middle of the work cell as shown in Fig. 2. Utilizing the User Datagram Protocol (UDP), the two laptops exchange files with a constant size of 60,000Bytes via an access point operating and consequently interfering on the channel. Interference traffic specifications used are shown in Table II while sweeping on the interfering node's sampling period. The degree of interference is quantified through sweeping the UDP sampling rate to reach the maximum Interference Bit Rate achieving maximum tolerable value for the medium, thus the Interference Bit Rate is used as the main interference quantification metric.

The first case is where the two nodes are communicating on two non-interfering channels in the absence of interference. The goal of this scenario is to demonstrate and verify the functionality of the two models built. In the first application scenario, interference will be only affecting one channel. Finally, interference is applied to both communication channels with the same physical model maintained during the scenario. The effect of interference is expected to be more apparent on the PRP system.

TABLE II. INTERFERENCE SYSTEM MODEL SPECIFICATIONS

Parameter	Value
Transmission Power	2.5mW
Distance Between Nodes	2m
Channel Sensitivity	-95dBm
Signal Attenuation Threshold	-100dBm
Payload Size	60,000Bytes
System Transport Layer Protocol	UDP

B. System Performance Metrics

Latency: the time a packet takes to move from the transmitter to the receiver. During each one of the 33 seeds, average latency was calculated and analyzed for each channel plus the PRP system.

Jitter: is the standard deviation of all latencies conducted during the whole simulation. Jitter was analyzed using the same way as latency, although standard deviation was used instead of average.

Maximum Delayed Packet: is the maximum delayed packet of each seed. This was evaluated in order to analyze packet drops. Maximum delayed packet was identified in each seed, and an average over the whole simulation was calculated.

IV. RESULTS

A. Interference Free(High and Low-Load)

The results show that all packets were transmitted successfully over the whole simulation time.

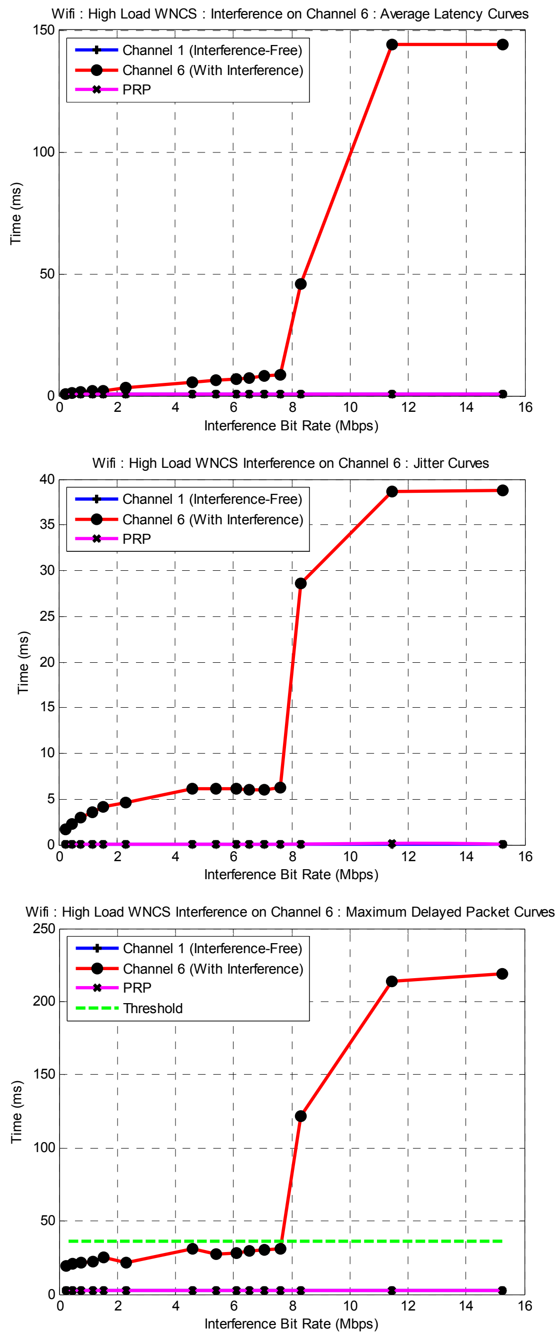

Fig. 3. Wi-Fi High-Load – single channel interference

Zero packets were dropped which is essential in all cases of this study. In addition, the latencies have not exceeded the limit of 36ms, which is 90% of the system's sampling period; a packet exceeding that limit is considered lost. The reason behind this was introducing a guard band to the system.

B. *High-Load Networked Control System*

1) IEEE 802.11g (Wi-Fi)

Applying interference only on one channel, the PRP system has led to a better performance regarding the average latency (Fig. 3).

The PRP system latency curve is a straight line identical to that of the interference-free channel, since the interference is only affecting one channel.

Beyond a bit rate of 7.6Mbps, the interfering nodes start to have a strong influence. The latency values of the channel under interference start to increase; this is due the fact that the contention level in the medium is increased. In addition to the average latency, the average jitter of the PRP system demonstrates improved performance and more immunity in comparison to the single channel system. The average jitter of the channel under interference is higher than that of the PRP system: this is because the PRP system receives the minimum delayed packet thus its latency values deviate at reduced ranges compared to that of the channel under interference.

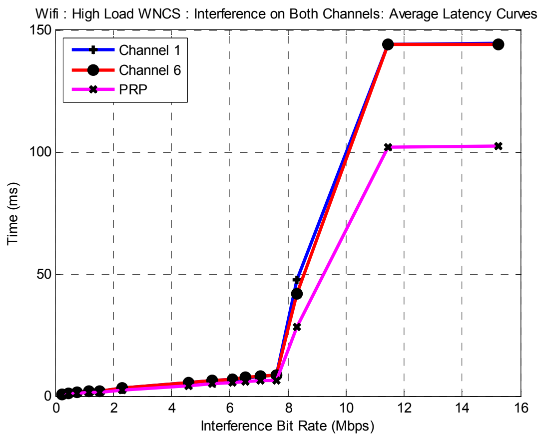

Fig. 4. Wi-Fi High-Load – dual channel interference

With interference on both channels of the Wi-Fi system, the benefits of using PRP are still there, but with a lesser effect because both channels are subjected to interference. It also illustrates that after a certain bit rate, the effect of the interference is more apparent. Figure 4 portrays a latency improvement of 21%, while the improvement of PRP on interference on one channel is 82%. Therefore, there is a substantial decrease of 61%.

2) IEEE 802.15.4 (ZigBee)

Figure 5 shows that the addition of PRP using ZigBee also leads to better results in latency, jitter, and maximum delayed packet when interference is applied on a single channel. The results are as expected due to the fact that the receiving node accepts the packet with the earliest arrival time. The graphs also illustrate slightly better results between the PRP and the interference-free channel because of the reason previously mentioned.

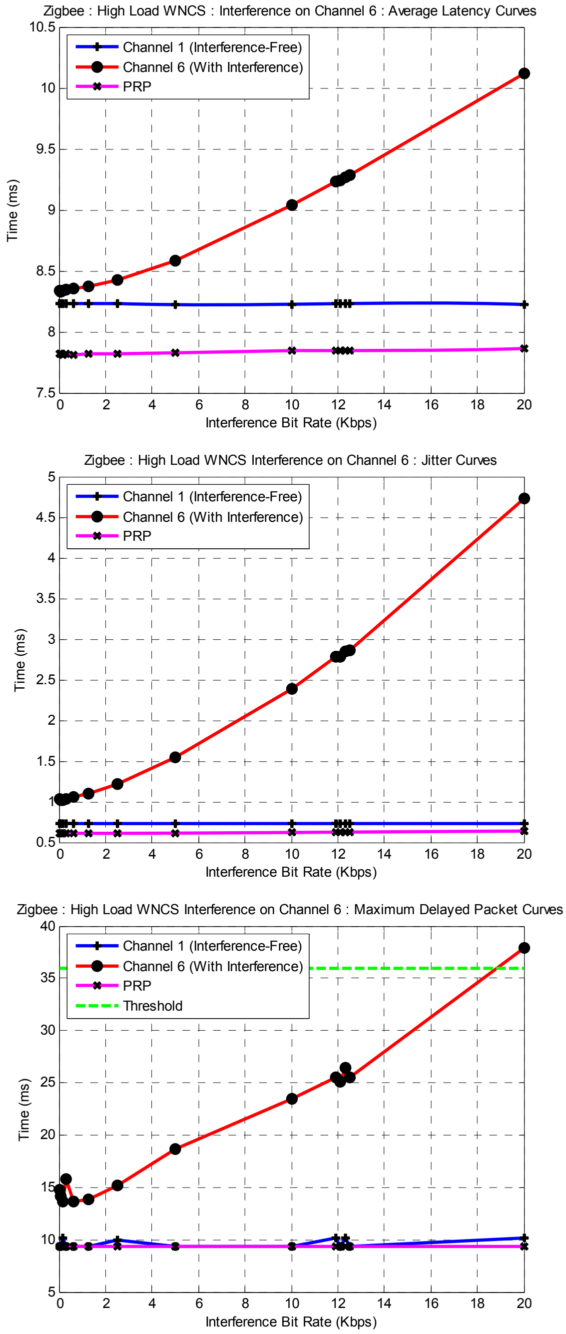

Fig. 5. ZigBee High-Load – single channel interference

Next, interference is applied to both ZigBee communication channels with the same physical model maintained during the scenario. The effect of interference is expected to be more apparent. On the other hand, PRP is not expected to improve the system's performance as much as in the previous scenarios. As discussed earlier the advantage of a PRP model is that if there is interference on one channel, which would have a negative impact on the latency, the system could still rely on the other channel. However, in the scenario where there is interference on both channels (Fig. 6), the latency ought to increase when compared with a PRP system with interference on only one channel.

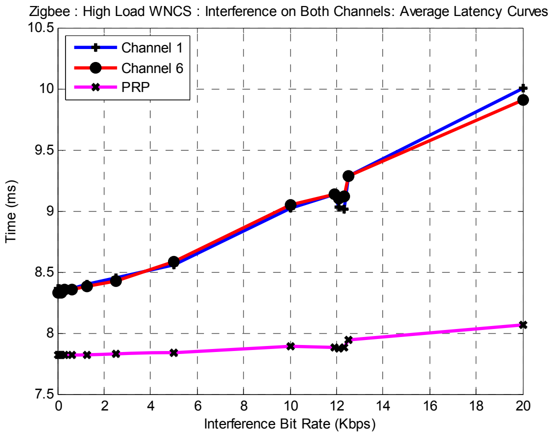

Fig. 6. ZigBee High-Load – dual channel interference

C. *Low-Load Networked Control System*

1) IEEE 802.11g (Wi-Fi)

Similar to the previous application the PRP system illustrated significant performance improvement compared to the single channel system in the three key indicators average latency, jitter, and packet loss.

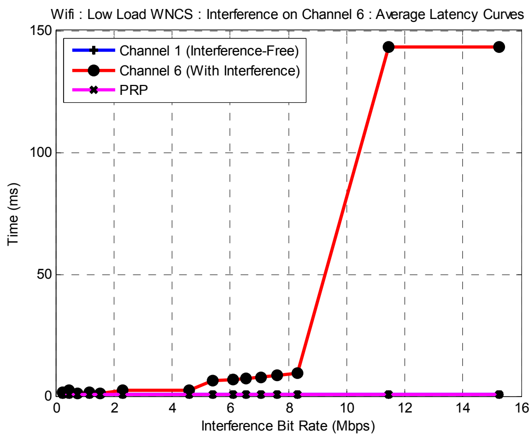

Fig. 7. Wi-Fi Low-Load – single interference

Figure 7 shows that the new improvement, in comparison to the High-Load application, is the ability of the single channel system to tolerate interference up to 8.3Mbps. This is an obvious consequence of increasing the sampling period of the control application to 1s instead of 40ms.

With interference on both channels in the Low-Load application, Wi-Fi maintains its high performance and reliability due to the fact that Wi-Fi provides a high transmission data rate exceeding the demands of the Low-Load application. The system now is even more tolerant to interference compared to the previous application, which is logical because of the same reasons mentioned previously.

2) IEEE 802.15.4 (ZigBee)

As expected with interference on only one channel, PRP has continued to improve the system's performance in latency and jitter. Figure 8 illustrates that the PRP system's performance is close to that of the interference-free channel as observed in previous scenarios. The major difference was the system's immunity against interference. With the system sending less frequently, less congestion on the channel occurs.

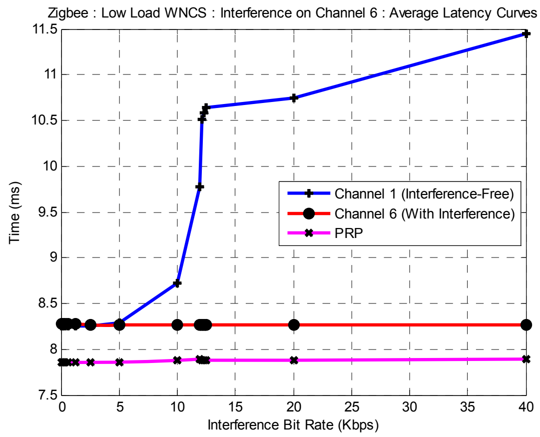

Fig. 8. ZigBee Low-Load – single interference

The system remains immune against increases in jitter. The deviation of the PRP system is still low due to the fact that the node accepts the earliest arriving packet. Concerning packet losses, the system still maintains the fact that no packet exceeds the system's sampling period. Additionally, the threshold at which dropped packets are observed has increased. The threshold has increased to 20Kbps; this means that the system is more immune against interference. This was expected because of less congestion on the channel.

With interference applied on both channels, results have shown that the increase in latency is not as large because there is less congestion. Moreover, the interference threshold is still greater because of the increase in the sampling period. With Zigbee's low transmission data rate, the Low-Load application allows the system to perform better in the presence of interference. Similar to all previous cases, PRP sustains the benefits that it adds to the system. The results show enhancement in performance due to PRP, with the PRP producing better results than the other two channels considered individually in all three metrics.

V. PROTOCOL COMPARISON

In order to evaluate the two protocols and to quantify the improvement to their performances due to the addition of PRP, percentage improvement in latency was calculated and compared to those of the interference-free system. With zero packet drops guaranteed, latency could be considered as the most important metric to compare the performances of both systems. As shown in Fig 9, Wi-Fi had a significant improvement of up to 82% with interference on one channel compared to up to 11% improvement in ZigBee. The percent improvement of Wi-Fi severely drops as interference is applied to both channels, with ZigBee almost maintaining its performance with 13% improvement in latency. There are only minor differences in improvement between the High-Load and the Low-Load application. Overall it can be stated, that PRP yields higher improvements with Wi-Fi than ZigBee due to its higher data rate.

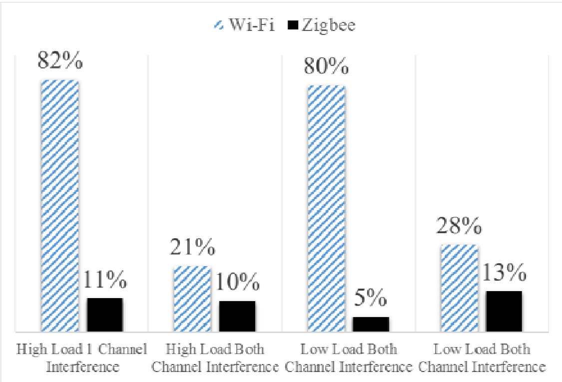

Fig. 9. Comparison of improvements

VI. CONCLUSION

The concept of PRP was applied to two different Wireless Networked Control System applications using different standards, Wi-Fi and ZigBee. Interference was applied and it was evident that PRP has significantly improved both systems' performances. Improvement was seen in all three metrics (Latency, Jitter, and Maximum Delayed Packet) used. It was shown that both systems have a good interference tolerance until a certain interference bit rate. Due to its lower data rate capability, ZigBee shows packet drop at much lower interference rates than Wi-Fi. Although PRP-WLAN maintains better performance than PRP-ZigBee, it became clearly visible that compared to PRP-WLAN, PRP-ZigBee shows a much better latency stability on the combined channels when interference is applied to both channels simultaneously. Note, all presented latencies include: packet transmission, propagation, encapsulation, decapsulation, and queuing delays.

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