On the Performance of a PRP-WLAN Enabled Wireless Backbone

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Abstract: - This paper investigated a 1-out-of-2 controller fault-tolerant system composed of two industrial workcells. Improving the performance and the reliability of the employed IEEE 802.11g wireless backbone was the main focus of this study. The approach taken to achieve this goal is the application of parallel redundant diverse wireless communication. A parallel redundant wireless backbone that interconnects two industrial workcells with a large number of sensors and actuators is modeled and simulated with the OPNET Network Modeler and its performance characteristics evaluated. For all studied system performance metrics, it was shown that the PRP-WLAN backbone is superior to a single-channel implementation under all investigated interference scenarios.

Key-Words: - Parallel Redundancy, Wi-Fi, PRP-WLAN Backbone, OPNET, Factory Automation, 802.11

1 Introduction

Industrial automation is usually categorized into process automation (PA) and discrete factory automation (FA) [1, 2]. A typical application of wireless systems in both areas is the connection of machine parts or machines in difficult environments. In contrast to wired communication systems, wireless systems achieve low installation cost and high reliability, especially as for example compared to the connection of movable machine parts by trailing cable systems, slip rings or sliding contacts. In these cases, wireless solutions can dramatically improve installation and maintenance costs, wear and thus reliability.

Component providers of industrial wireless communication systems in the factory automation use typically available technologies, such as WLAN [3], Bluetooth [4] or ZigBee [5] conforming to standard transceiver components. On top of this, proprietary protocol extensions are added. Well-known examples are the IEEE 802.11 based IWLAN system of Siemens [6], the IEEE 802.15.1 based WISA system of ABB [7] and both the IEEE 802.15.4 based WirelessHART and ISA 100.11a systems by the HART communication foundation and the International Society of Automation (ISA), respectively. It is important to note that, due to the real-time nature of most industrial applications, timely packet delivery with minimal or even no packet losses must always be guaranteed by the employed communication system [8].

One of the currently commercially available Wireless Networked Control System (WNCS) implementations, introduced in [7], is the Wireless Interface for Sensors and Actuators (WISA). The system uses a modified non-standard version of Bluetooth [4] for its underlying communication protocol and supports up to 30 sensors & actuators. Moreover, the system is also designed to provide wireless powering of nodes within the system. The communication aspect of this system is currently undergoing standardization as the Wireless Sensor-Actuator Network [9] standard.

Reference [10] introduced an alternative WNCS implementation based on the unmodified IEEE 802.11b Wi-Fi [3] and Ethernet [11] protocols and utilized [7] as its benchmark. The introduced WNCS is composed of several sensor-actuator pairs communicating over IEEE 802.11b through two access points with a single controller in a 3×3m workcell [12].

With the development of WNCSs for real-time industrial applications and due to the shared nature of the wireless medium typically operating in the unlicensed Industrial, Scientific and Medical Band (ISM), the assessment of interference has started to gain widespread interest.

It was concluded in [7] that factory floor interference arising from activities such as spot/arc welding as well as from mechanical vibrations does not impact the frequencies belonging to the 2.4GHz ISM band. Thus, only other ISM band systems are potential sources of external interference.

Reference [13] investigated the impact of interference on real-time communication for IEEE 802.11-based mesh networks through simulation studies. While in [14], the WNCS presented in [10] was further enhanced and, moreover, a study of different types of interference, such as network congestion, medium congestion and intentional jamming, was conducted.

Several further studies focused on the concatenation of multiple identical WNCS workcells utilizing a wired backbone for inter-cell communication [15-18]. In [15], the concatenation of two adjacent workcells was modeled. It was found that the minimum inter-cell separation needed for correct operation was 2m. This separation distance was eliminated in [16] using a novel channel allocation scheme. Finally in references [17, 18], controller fault-tolerance was implemented over the concatenated workcells.

Reference [19] improved upon the fault-tolerant system in [17] by migrating from a wired Ethernet backbone to a completely wireless backbone implementation based on IEEE 802.11g. Furthermore, the effect of interference was studied on the employed workcells. However, the effect of external interference on the wireless backbone was not investigated.

Due to the critical nature of the backbone for industrial WNCSs and the challenges imposed by wireless communication links, the reliability of the backbone develops into a particularly important issue especially under external interference. One of the methods to increase the reliability and performance of wireless links is by applying diversity in the form of the redundant transmission of information over multiple stochastically uncorrelated channels [20]. For packet transmissions, a possible diversity scheme able to yield specific gains utilizes parallel redundancy in the space and frequency domains [21]. Reference [22] presented Parallel Redundant WLAN (PRP-WLAN) which used the Parallel Redundant Protocol (PRP) as per IEC 62439-3 utilizing splitter and combiner units on the Ethernet level. Experimental studies carried out in [23, 24] showed significant improvements. The improvements gained through the utilization of a dual-radio approach were further verified through a simulation study in [25] for several investigated performance metrics.

In this paper, a model similar to the one described in [19] is going to be investigated and the focus will be on the reliability of the backbone itself. It will be shown how to apply PRP on the wireless backbone link. The proposed system will be simulated using the OPNET Network Modeler [26]. Clearly, the fault-free scenario is expected to have more traffic due to the absence of the extra traffic (needed to achieve fault-tolerance) being exchanged over the backbone in the event of a controller failure as in [18, 19]. As such, this paper will focus on the fault-free scenario.

It is expected that applying PRP over the wireless backbone will lead to better performance and interference tolerance. As such, the focus of this study is on quantifying this improvement in performance as well as the maximum interference tolerable by the system.

Moreover, it will be shown that the PRP-WLAN backbone will remain operational despite of the heavy congestion caused by the watchdog traffic with its stringent delay requirement.

2 Previous Work

The WNCS system described in [19] consists of two identical adjacent workcells each composed of several sensor-actuator pairs with a single controller responsible for each workcell. The sensor and actuator nodes belonging to each workcell communicate wirelessly over two access points using IEEE 802.11b with their workcell's respective controller which, in turn, is connected to the cell's access points via switched Ethernet.

A wireless backbone, using IEEE 802.11g, was implemented to connect between the two adjacent workcells and was used for inter-cell communication. Controller fault-tolerance able to tolerate the failure of any one of the two present controllers (1-out-of-2) was implemented in [19]. In order to implement fault-tolerance, extra traffic exchanged between the two cells was required. Such extra traffic includes watchdog packets being frequently exchanged between the two workcell's controllers as a failure detection mechanism. Additionally, to allow for the remaining controller to take over the operation of the other workcell in case of a controller failure, all intra-cell information being generated by the sensor nodes was duplicated and transmitted to both cells' controllers.

Moreover, in [19], the effect of external interference on the performance of the individual workcells was investigated. However, the reliability of the wireless backbone link as well as the impact of external interference on it was not investigated.

One particular method of improving the reliability and performance of wireless links is parallel redundant transmission of information over multiple independent wireless channels. Reference [25] showed how the use of PRP-WLAN results in substantial improvement in overall performance and reliability over single-channel transmissions. The model simulated in [25] was formed of a single source-sink pair communicating via IEEE 802.11g over two non-interfering wireless channels. Data transmitted by the source node is duplicated over the two independent wireless channels. On a packet-by-packet basis, the first arriving packet at the sink node is used while the later arriving duplicate is discarded. The proposed model was simulated in the absence of external interference and the PRP-WLAN implementation was proven to adhere to the control system's requirements.

Moreover, several interference scenarios were investigated in [25] including single-channel interference over each of the two utilized wireless channels individually as well as simultaneous interference over both wireless channels. In all simulated interference scenarios, PRP proved superior to a single channel implementation for all investigated performance metrics.

3 Proposed Model

In this paper, the performance characteristics of inter-workcell PRP over a wireless backbone will be investigated over two concatenated workcells. Wireless backbone links are ideal candidates for the application of PRP due to the critical nature of such links stemming from the stringent control system constraints regarding packet loss and packet deadlines.

The control system constraints on the wireless backbone are even more stringent for the additional traffic necessary for the implementation of fault-tolerance at the controller level (1-out-of-2). As such, the performance of PRP over the backbone will be studied for such scenario. In all cases, performance improvements offered by PRP for the wireless backbone will be evaluated and consequently quantified by the maximum interference file-size tolerable under different interference scenarios.

3.1 Model Description

The system proposed in this work (shown in Fig. 1) consists of two industrial workcells each composed of a controller (K), several Sensor-Actuator (SA) pairs and a single Access Point (AP). The two workcells under study are concatenated at a distance of 3m with 1m added to the 2m minimum inter-cell distance as a safety margin similar to that used in reference [19].

The transmit power and Packet Reception Power Threshold (PRPT) of the various nodes belonging to each cell in addition to the inter-cell separation distance between the workcells were specifically chosen so as to minimize the interference between the two cells.

A wireless backbone is utilized to connect between the two workcells as in [19] as opposed to utilizing a wired backbone. Moreover, for the proposed system, the aforementioned PRP-WLAN concept which was studied in [25] is applied to this critical wireless link interconnecting the two workcells. Due to the high amount of traffic as well as the stringent control system constraints on the backbone, PRP-WLAN was employed across the backbone.

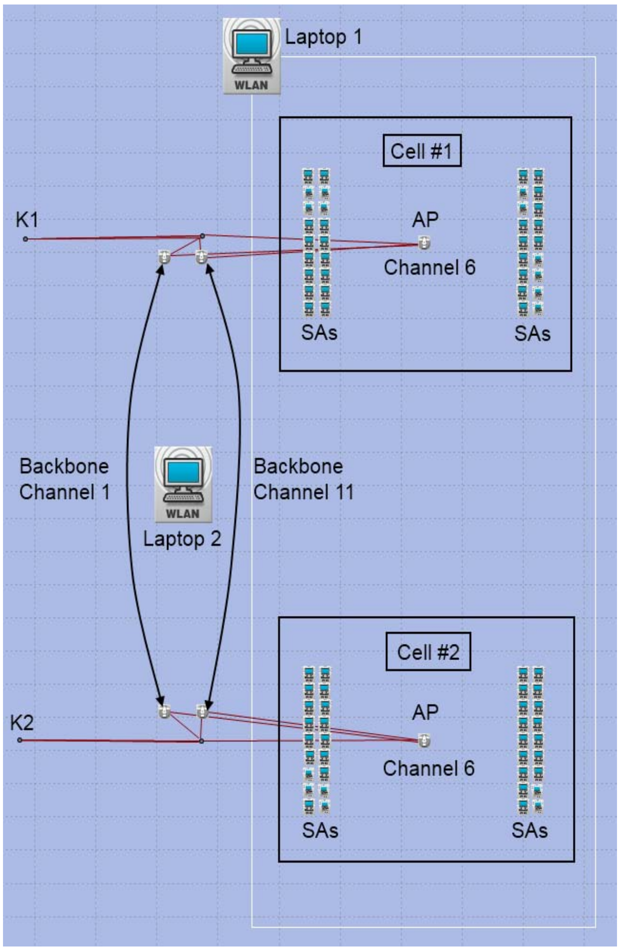

Figure 1. Proposed Model Overview

Each workcell's AP operates over IEEE 802.11g similar to the system in reference [18], the additional throughput offered by IEEE 802.11g allows a single AP to handle the load of an entire workcell instead of having to utilize two APs per workcell as in [10]. Additionally, the use of a single IEEE 802.11g channel for the workcell and reusing the same channel across the other cell frees up the two remaining non-interfering IEEE 802.11g channels for the implementation of the PRP-WLAN

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backbone. Thus, all three non-interfering IEEE 802.11g channels (Ch. 1, Ch. 6 and Ch. 11) are utilized and the following channel allocation with minimal interference between wireless channels is achieved: Channel 6 for use inside the workcells, Channels 1 & 11 for use in the PRP-WLAN backbone as shown in Fig. 1.

In each workcell, the sensors are responsible for sensing the environment and subsequently transmitting their readings in the form of a 10Byte word to all controllers. The 10Byte word simulates ON/OFF control with additional room for extra possible information. The controller then receives those control packets and, after processing, sends a control word to each one of the actuators that is currently being managed by that controller at that particular instance of time. For the aforementioned communication between sensors, controllers and actuators, the system sampling period is the same as that in [14] (40ms) with a 10% guard time taken into account thus making the control system's total end-to-end delay constraint equal to 36ms. All workcell control traffic is transmitted over the User Datagram Protocol (UDP) instead of the Transmission Control Protocol (TCP) to decrease the congestion on the network due to acknowledgments [27].

In order to detect a failure at the controller level, watchdog packets are exchanged between each pair of controllers every 20ms (half the system's 40ms sampling period). When a controller fails, the lack of received watchdog packets indicates the failure occurrence to the other controller. Consequently, the remaining controller takes over the operation of the other cell.

Table 1. Model Specifications Summary

Parameter	Value
Number of Sensors/Actuators	36
Number of Controllers	2
Number of Workcell APs (Channels)	2 (Ch. 6 reused)
Number of Backbone APs (Channels)	4 (Ch. 1 & 11)
Wireless Protocol	IEEE 802.11g
Transmission Data Rate	54Mbps
Node Transmit Power	1mW
Sampling Period	40ms
Sampling Deadline	36ms
Watchdog Period	20ms
Watchdog Deadline	18ms
Control Word Packet Size	10Bytes
Control Transport Layer Protocol	UDP
Watchdog Packet Size	46Bytes
Watchdog Application Layer Protocol	FTP
Node Short Retry Threshold	255
AP Buffer Size	256000bits

Thus, another important and even stricter end-to-end delay constraint is that for the watchdog packets. Similarly, a 10% guard time is taken into consideration thus making the watchdog's end-to-end delay constraint equal to 18ms.

In addition to the aforementioned delay constraints, which the control system must treat as hard deadlines, the control system must suffer no loss of control packets. A single control packet either lost due to a failed transmission or over-delayed due to congestion and queuing would cause the failure of the control system. A summary of the proposed system's model specifications are presented in Table 1.

3.2 Interference Scenarios

In order to evaluate the performance improvements offered by PRP when applied to the wireless backbone, the system was subjected to different interference scenarios. Note that, in all scenarios, the workcells themselves were not subjected to interference.

To simulate single channel interference, a laptop pair exchanging files over FTP is added, as shown in Fig. 1, in order to cause congestion over the shared Wi-Fi medium as in references [14, 25].

The employed interference scenario represents the impact of medium congestion caused by traffic being exchange by an external laptop pair communicating on a different neighboring network but over the same wireless channel in the ISM band. ISM band interference was employed due to the fact that it is the only possible source of external interference on the wireless system given that typical factory floor operations such as welding do not cause interference on the ISM band as concluded in [7].

In order to maximize the interference over the backbone, one of the laptops is positioned in the middle of the wireless backbone link. Similarly, to simulate dual channel interference, an extra laptop pair communicating over the second channel is added. A summary of the interference model specifications in presented in Table 2.

Table 2. Interference Model Specifications Summary

Parameter	Value
Inter-Request Time	0.5s
Wireless Protocol	IEEE 802.11g
Transmission Data Rate	54Mbps
Interference Node Transmit Power	5mW
Application Layer Protocol	FTP

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3.2.1 Interference-Free Scenario

In order to test the developed model and to establish a benchmark against which the performance of the PRP-enabled wireless backbone can be compared, the proposed system was first simulated in the absence of any external interference.

In this scenario, the performance characteristics across the individual channels forming the backbone are expected to be almost identical. This is due to the symmetrical nature of the traffic which is duplicated on the underlying non-interfering wireless channels belonging to the PRP-enabled backbone.

It will be shown that, even in the absence of interference, the performance of the PRP-enabled backbone is superior to that of an equivalent single-channel backbone.

3.2.2 Single Channel Interference

Interference over one of the PRP-enabled backbone's underlying channels was first investigated. Interference was applied to Channel 1 by adding a laptop pair communicating independently over the same channel thereby congesting the medium as previously mentioned. The file size communicated by the laptop pair is used to quantify the interference on the channel.

The same simulation experiments were then repeated but with interference on the other underlying channel (Channel 11) in order to verify the results from Channel 1. Due to the symmetrical nature of the traffic across the two underlying channels of the backbone, it is expected that the results would be almost identical to those with interference on Channel 1.

For the single channel interference scenarios, it is expected that the overall PRP performance characteristics would not be adversely affected by the applied interference due to the method by which the PRP-enabled backbone operates.

3.2.3 Dual Channel Interference

Finally, a worst-case interference scenario is applied to the proposed system whereas both the PRP-enabled backbone's underlying channels are subjected to interference simultaneously. To that end, an extra laptop pair is added to that of the single channel interference model communicating over the second underlying wireless channel.

Due to the nature of the applied interference, it is expected that the performance improvements offered by PRP would diminish.

For all simulated scenarios, the interference tolerance of the proposed system was quantified by the maximum interference file-size tolerable while satisfying the aforementioned control system criteria.

3.3 System Performance Evaluation Metrics

For each simulation scenario, in order to evaluate the performance of the system and to quantify the improvements offered by a PRP-enabled backbone, three performance metrics were studied. In each case, the performance of the PRP-enabled backbone was compared to an equivalent single-channel backbone implementation. The three metrics are:

Maximum End-to-End Delay: defined as the maximum observed control packet end-to-end delay for all transmissions across the backbone. This metric is extremely important for the evaluation of the control system under study due to the hard nature of the control system deadlines. In other words, any over-delayed packet that misses the required system deadline is considered lost consequently leading to the failure of the control system.

For the system under study, there are two main end-to-end delay constraints: the workcell control packet end-to-end delay constraint (40ms) as well as the watchdog packet end-to-end delay constraint (20ms). In both cases a 10% guard time is taken into account to allow for some margin of error. Thus, the control system is considered to have failed if any workcell control packet exceeds 36ms or if any watchdog packet exceeds 18ms.

Latency: defined as the average end-to-end delay of all packets sent over the PRP-enabled backbone. This metric serves as a measure of the average overall system performance.

Jitter: defined as the packet delay variation of all packets transmitted over the PRP-enabled backbone. This metric is calculated as the standard deviation of all packets sent over the backbone.

For all the aforementioned metrics, a 95% confidence analysis is carried out across 33 different simulations seeds to offset the non-deterministic nature of the employed wireless protocol.

4 Results and Analysis

In this section, OPNET simulation results for the proposed system are presented. As previously mentioned, several interference scenarios are considered: the interference-free scenario, single channel interference scenarios (individually on both underlying wireless channels of the PRP backbone) and dual channel interference (on both channels simultaneously).

It is important to note that, in all simulations, the system experienced no packet drops and that all presented delays include packet propagation, transmission, queuing, encapsulation and decapsulation delays. Processing delays, which are application dependent and hard to quantify, were assumed to be negligible for the purpose of the analysis based on the study in [28].

4.1 Analysis Methodology

For all presented scenarios, the aforementioned system performance evaluation metrics (Maximum Packet End-to-End Delay, Latency and Jitter) were analyzed and the performance benefits of the PRP-enabled backbone quantified. A 95% confidence analysis was carried out for all presented results, 33 seeds were conducted for each simulation scenario. From this analysis, all values in the figures represent the upper bound of the resulting confidence interval.

4.2 Interference-Free Scenario

In order to validate the operation of the proposed model and ensuring that the aforementioned control system criteria are not violated, the proposed model was simulated without applying external interference. The maximum end-to-end delay results for the workcells employed in the proposed system are presented in Table 3 where S->K represents the maximum delay from a sensor to the controller, K->A represents the maximum delay from the controller to an actuator and S->K->A represents the maximum total end-to-end delay.

Table 3. Summary of Workcell Results

Cell #	Max Delay S->K (ms)	Max Delay K->A (ms)	Total Delay S->K->A (ms)
1	[3.0;.3.6]	[16.5; 19.0]	[19.5; 22.6]
2	[2; 2.5]	[15.9; 18.5]	[17.9; 21.1]

From the results in Table 3, it is apparent that both control workcells fulfill the control system constraints; no control packets were lost and both cells experience a total end-to-end delay less than the system control deadline.

Additionally, the proposed system must meet the previously mentioned watchdog packet delay deadline. Each cell's controller transmits watchdog packets to that of the other cell. The transmitted watchdog packets are duplicated over the backbone. The calculated system performance evaluation metrics for the watchdog backbone traffic are presented in Table 4 where K*i* is the controller in cell *i*.

Table 4. Summary of PRP-Enabled Backbone Results

Watchdog Destination	Maximum Delay (ms)	Latency (ms)	Jitter (ms)
K1 Ch. 1	[6.7; 7.0]	[4.6; 4.8]	[0.48; 0.5]
K1 Ch. 11	[6.7; 7.0]	[4.7; 4.8]	[0.46; 0.48]
K1 PRP	[5.8; 5.9]	[4.4; 4.5]	[0.37; 0.38]
K2 Ch. 1	[6.8; 7.0]	[4.7; 4.8]	[0.47; 0.49]
K2 Ch. 11	[6.6; 6.9]	[4.7; 4.8]	[0.46; 0.48]
K2 PRP	[5.8; 6]	[4.4; 4.5]	[0.37; 0.38]

From the results in Table 4, it is seen that the watchdog packet deadlines are met. All watchdog packets arrive at each controller within the required deadline.

Moreover, as expected, the PRP performance characteristics are better than any single channel taken on its own across all the three metrics even without the presence of interference. PRP improves the experienced maximum end-to-end delay by 13%, the experienced latency by 6% and the experienced jitter by 20%.

The remaining simulation scenarios will investigate the performance impact of different interference scenarios on the PRP-enabled backbone. Consequently, the individual workcells, which are operating on a different non-interfering wireless channel, will not be affected thereby ensuring that the individual workcell's control packet delay deadline is always met.

4.3 Single Channel Interference

Interference was applied on each of the backbone's two underlying channels individually. The file-size being exchanged by the interfering laptop pair was swept in order to quantify the impact of external interference on the backbone link. As expected, as the interference file-size was increased, the performance of the channel under interference starts to decrease due to the congestion of the wireless medium.

4.3.1 Interference on Channel 1

For this scenario, interference was applied only on Channel 1. Figures 2, 3 and 4 display the simulation results of the interference file-size sweep for the three aforementioned system performance metrics.

Figure 2 shows the maximum end-to-end delay result curves for the watchdog packets over the PRP-enabled backbone. For all simulated interference file-sizes, the PRP system provides better performance than any of the two underlying channels taken individually as expected. The experienced percentage improvement in performance of PRP was at least 31% for this metric. This is due to the fact that the PRP system makes use of the earliest arriving packet on any of the two underlying channels on a packet-by-packet basis.

For the same reason, the PRP system is, moreover, completely immune to single channel interference. The PRP system will always have a result better than or identical to that of the other channel which is not under interference. The threshold, in this case, is fixed to 18ms which is the watchdog packet delay deadline. If a single channel system were employed then the maximum interference file-size tolerable by the single channel under interference before exceeding the 18ms deadline was found to be 28Kbytes. The use of PRP over the backbone overcomes this limitation and provides complete immunity under single-channel interference.

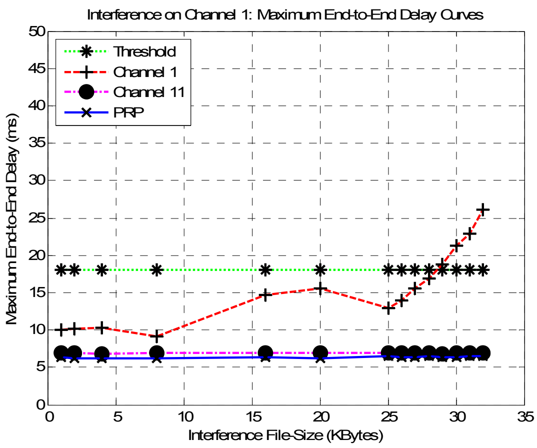

Figure 2. Maximum Watchdog End-to-End Delay Curves (Interference on Channel 1)

Figure 3 illustrates the resulting latency curves. Similarly, the performance of the PRP system is always better than that of the underlying wireless channels taken individually. For this metric, PRP showed a percentage improvement in performance of at least 9%.

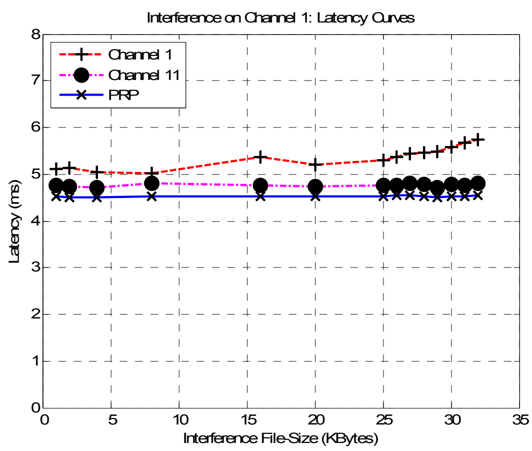

Figure 3. Watchdog Latency Curves (Interference on Channel 1)

Figure 4 shows similar improvements in the case of jitter. PRP consistently offers less jittery packet transmissions. In this case, PRP showed a percentage improvement of at least 35%.

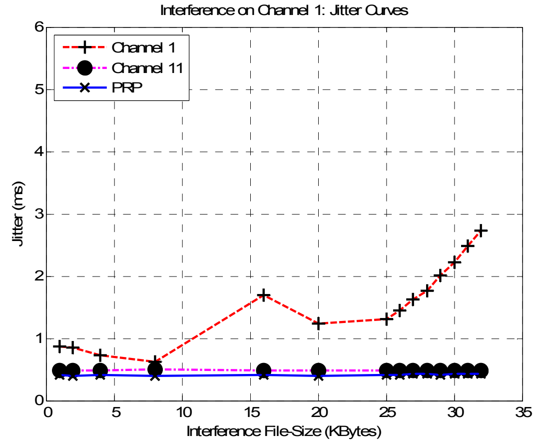

Figure 4. Watchdog Jitter Curves (Interference on Channel 1)

4.3.2 Interference on Channel 11

In order to verify the previous single channel interference results, the same interference scenario was repeated with interference on the other underlying channel (Channel 11). Figures 5, 6 and 7 show the simulation results for the three system performance metrics during the interference file-size sweep on Channel 11.

As expected, the exhibited PRP performance with interference on Channel 11 is almost identical to that with interference on Channel 1. The observed single channel maximum tolerable interference file-size was also found to be 28Kbytes. The experienced percentage improvement in performance for the PRP system compared to the channel under interference was found to be at least 30%, 6.2% and 32.1% for the three system performance metrics: Maximum End-to-End Delay, Latency and Jitter respectively.

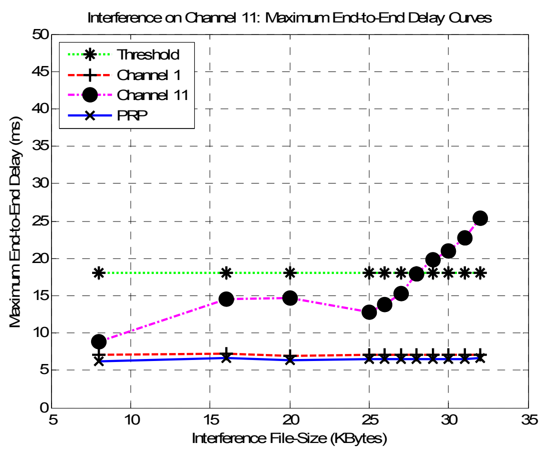

Figure 5. Maximum Watchdog End-to-End Delay Curves (Interference on Channel 11)

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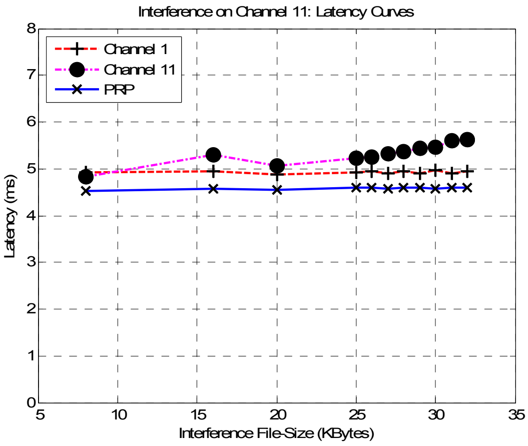

Figure 6. Watchdog Latency Curves (Interference on Channel 11)

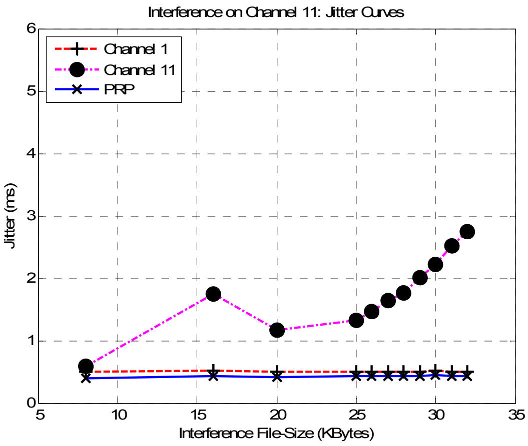

Figure 7. Watchdog Jitter Curves (Interference on Channel 11)

4.4 Dual Channel Interference

Finally, for the worst-case interference scenario, interference was applied on both underlying channels of the PRP-enabled backbone simultaneously.

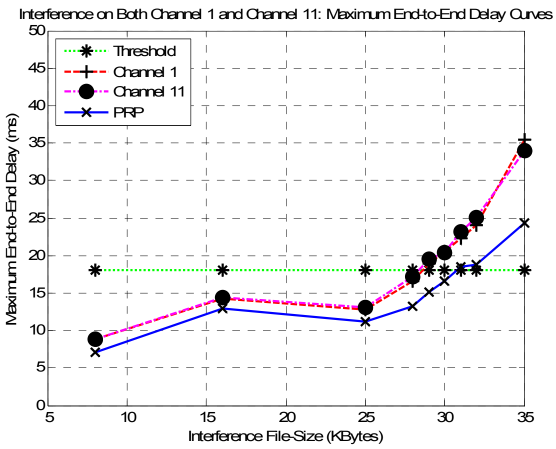

Figure 8. Maximum Watchdog End-to-End Delay Curves (Interference on both Channel 1 and 11)

Figures 8, 9 and 10 illustrate the resulting file-size sweep for the three system performance metrics with both channels subjected to interference.

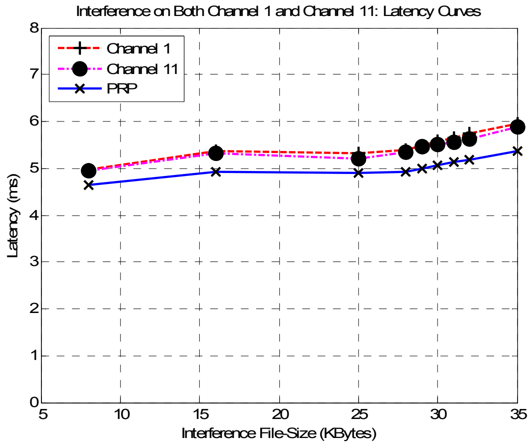

Figure 9. Watchdog Latency Curves (Interference on both Channel 1 and 11)

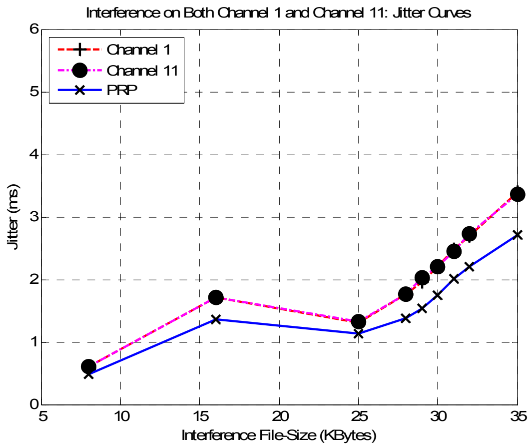

Figure 10. Watchdog Jitter Curves (Interference on both Channel 1 and 11)

As expected, the PRP system still continues to show improvement over each single underlying channel however at a more diminished capacity. From the previous figures, the percentage improvement in performance experienced by the PRP system compared to the channels under interference was found to be at least 8.9%, 6.7% and 13.4% for the three system performance metrics: Maximum End-to-End Delay, Latency and Jitter respectively.

It is important to note that, since both underlying channels are subjected to interference simultaneously, PRP is no longer completely immune to the effect of interference. As such, as the interference file-size is increased, the maximum end-to-end delay experienced over the PRP system starts to increase until it exceeds the watchdog's delay deadline. The maximum interference file-size tolerable by the overall PRP system was found to be 30KBytes, an increase of 7% over that for a single channel system.

4.5 Results Summary

In summary, in all simulated interference scenarios, PRP offers better performance characteristics across all three studied system performance metrics (Maximum End-to-End Delay, Latency and Jitter).

PRP demonstrates complete interference immunity when interference is applied to only one of its two underlying channels. This is due to the fact that PRP always makes use of the earliest arriving packet over the two channels, one of which is without interference, on a packet-by-packet basis.

For the worst case interference scenario, where interference is applied on both of the underlying channels of the PRP backbone simultaneously, PRP still offers superior performance characteristics but loses its interference immunity.

Tables 5 and 6 show the maximum watchdog end-to-end delay results for the single channel interference and dual channel interference scenarios respectively. The presented interference file-size values correspond to those at: the worst percentage improvement, the maximum tolerable interference file-size and at the best percentage improvement respectively.

Table 5. Maximum End-to-End Delay Results for Interference on Channel 1 Only

File-Size (KBytes)	Channel 1 (ms)	Channel 11 (ms)	PRP (ms)
8	[8.53; 9.08]	[6.71; 7]	[6.01; 6.21]
28	[15.93; 16.95]	[6.67; 6.9]	[6.19; 6.44]
32	[23.04; 26.08]	[6.65; 6.9]	[6.18; 6.45]

Table 6. Maximum End-to-End Delay Results for Interference on both Channel 1 and 11

File-Size (KBytes)	Channel 1 (ms)	Channel 11 (ms)	PRP (ms)
8	[8.24; 8.86]	[8.3; 8.83]	[6.82; 7.14]
30	[19.41; 20.53]	[19.16; 20.44]	[15.78; 16.66]
35	[32.73; 35.48]	[31.33; 33.98]	[22.81; 24.41]

Table 7. PRP Percentage Improvement Summary (%)

Metric	Single Channel Interference		Dual Channel Interference	
	Worst	Best	Worst	Best
Maximum	30	73.6	8.9	28.2
Latency	6.2	18.3	6.7	8.8
Jitter	32.1	84.2	13.4	21.7

Table 7 presents a summary of the worst and best percentage improvements of PRP over the channel under interference, obtained from the previous figures, for all the system performance metrics under study.

5 Conclusion

Recent research interest has focused on the study of Wireless Networked Control Systems (WNCSs) for industrial applications. The advantages offered by wireless communication solutions such as ease of installation and maintenance as well as lack of cabling make them attractive to certain industrial applications. However, due to the shared nature of the wireless communication medium, its susceptibility to external interference and the typically stringent industrial control system requirements, significant emphasis must be placed on performance, reliability and fault-tolerance.

This paper investigated a 1-out-of-2 controller fault-tolerant system composed of two industrial workcells each with several sensor and actuator nodes. Simulations were carried out on the OPNET Network Modeler. The focus of the study was on the reliability and performance of the employed wireless backbone based on IEEE 802.11g. It was shown how PRP-WLAN could be applied to this critical wireless backbone link. Moreover, the performance improvements gained through the use of PRP were quantified based on investigated evaluation metrics (Maximum End-to-End Delay, Latency and Jitter).

Furthermore, the impact of external interference on the backbone link was studied and the maximum tolerable interference quantified under several interference scenarios namely single-channel interference and dual channel interference. For the scenarios where interference was applied on a single channel only, PRP consistently offered better performance for all three studied metrics as well as complete immunity to interference. For the PRP-WLAN backbone, Maximum End-to-End Delay attained an improvement of at least 30%, Latency improved by at least 6.2% while Jitter improved by at least 32.1% compared to the channel under interference.

For a worst-case analysis, where interference was applied to both channels simultaneously, PRP still showed superior performance. For the PRP-WLAN backbone, the percentage improvement for the three investigated system metrics was 8.9%, 6.7% and 13.4% respectively. Under this interference scenario, even though the PRP backbone is no longer perfectly immune to interference, it was shown that the maximum interference tolerable by PRP-WLAN backbone is 7% higher than a comparable single channel backbone implementation.

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It was shown that the use of PRP-WLAN across the backbone is superior to a single-channel implementation for all studied system performance metrics and under all investigated interference scenarios. In all simulated scenarios, the proposed system fulfilled the required control system constraints with no lost or over-delayed packets.

In all cases the system was proven to be operational despite of the heavy congestion caused by the watchdog packets as well as the stringent watchdog packet deadline. A 95% confidence analysis was carried out for all results presented in this work. All presented latencies include packet encapsulation, transmission, propagation, queuing and decapsulation.

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