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MEASUREMENT OF ZIGBEE WIRELESS COMMUNICATIONS IN MODE-STIRRED AND MODE-TUNED REVERBERATION CHAMBER

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Abstract—It is highly desirable to use advanced sensor networks to continuously monitor the structural health of an aircraft. It would be advantageous if the network was wireless to avoid the need for additional wire bundles and associated interconnects but the reliability of a suitable wireless channel in low loss enclosed structures needs to be understood. This paper reports on work undertaken testing the 2.4 GHz ZigBee wireless protocol in a mode stirred and mode tuned reverberation chamber. The results show that even for very low loss enclosures wireless communications is possible but only under very specific conditions. A higher loss chamber has more reliable communication channels, but even with loading there are large variations in packet error rates even between adjacent ZigBee channels.

1. INTRODUCTION

There has been much recent interest in the structural health monitoring of aircraft to help meet the significant challenges in maintaining and ensuring the safety of current and future aircraft [1–3]. The integration of advanced sensor networks for structural health monitoring offers the opportunity to continuously inspect critical components both on the ground and whilst airborne. It is desirable to make this sensor network wireless, since an increase in wiring and the associated interconnects would complicate maintenance and reduce the reliability of the system [4].

In a communication system the quality of the transmission is usually quantified by either the Bit Error Rate (BER) or the Packet Error Rate (PER), where a packet contains a number of bits. The

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BER is given by:

$$BER = 1 - \frac{N_{Rx}}{N_{Tx}} \tag{1}$$

where N_{Rx} and N_{Tx} are the total number of correctly received bits and transmitted bits respectively. The PER is the ratio of the incorrectly transferred data packets divided by the number of transferred packets. It is related to the BER by [5]:

$$PER = 1 - (1 - BER)^N \tag{2}$$

where N is the number of bits in the packet. A significant problem in implementing a wireless aircraft network is the propagation environment inside the aircraft. Of particular concern are low loss cavities that exist within an aircraft structure, where multiple reflections would occur from the walls increasing the mean delay spread and reducing the quality of transmission. Further a narrow equivalent bandwidth caused by uncorrelated resonant modes in the cavity would lead to inter-symbol interference and hence a higher BER and PER.

The ZigBee specification [6] is intended for RF applications requiring low data rates, long battery life and secure networking. The ZigBee specification is built on top of the IEEE 802.15.4 standard which specifies both the physical and MAC layers. The features of the ZigBee specification are given in Table 1.

Over the last few years ZigBee has been increasingly used in wireless sensor networks. Panitz et al. [7, 8] carried out an analysis of current wireless network technologies: IEEE 802.11, Bluetooth and ZigBee/IEEE 802.15.4. Their analysis has shown that ZigBee would be the most robust system in a resonant environment, because of its comparatively low data rate and high symbol period.

A reverberation chamber is a large cavity operating in a frequency range where a large number of resonant modes can be excited. The chamber is a screened room constructed to have minimum absorption

Table 1. ZigBee specifications.

Features	
Data Rate (Mbps)	0.25
Power Consumption	10–100 mW*
Spread Spectrum	DSSS
Number of Nodes	65 000
Encryption	128 bit AES

*The power consumption is reduced by using sleep mode and is dependent on the duty cycle.

of electromagnetic energy, so that in normal operation the decay time of the resonant modes would be long. Within the chamber there are normally one or two mechanical stirring devices which can be rotated continuously, this is referred to as mode stirred, or maintained in a fixed position, mode tuned. Reverberation chambers have been used to replicate Rayleigh or Ricean fading and to emulate multi path propagation [7].

A major concern in implementing a wireless system on an aircraft is the quality of the channels in an empty fuselage or equipment bay which, in electromagnetic terms, can be considered as cavities capable of supporting large numbers of resonant modes. Provided that a large number of modes can be supported in the aircraft cavity and the quality factor is similar then information regarding the quality of the wireless interconnect can be obtained using a reverberation chamber [5]. If the measurements are taken in the mode tuned reverberation chamber then small movements of the stirrer can be used to provide some insight into the effects of vibration on the quality of the communication channel.

A reverberation chamber has been used previously for assessing the performance of ZigBee [7–9]. In these studies the chamber has been loaded with absorber to reduce the quality factor (Q) and it was observed that the packet error rate reduced significantly as the Q reduced. In this paper we report on experimental work carried out in a reverberation chamber for both mode stirring and mode tuning, under loaded (reduced Q) and unloaded (high Q) conditions.

2. TEST ENVIRONMENT

The experimental work reported in this paper consisted of placing a transmitter and receiver inside a reverberation chamber. The reverberation chamber used is at the UK National Physical Laboratory (NPL) and has dimensions of $6.55\,\mathrm{m} \times 5.85\,\mathrm{m} \times 3.5\,\mathrm{m}$ with a vertical stirrer [10]. The stirrer has a gearing that enables 5000 steps for every complete rotation, thereby providing a resolution of 0.072 degrees. This very fine resolution was considered important to gain some insight on the effects of enclosure perturbation on the quality of the ZigBee communication channel.

If a mode stirred reverberation chamber is considered then it is common to characterize it in terms of a quality factor Q, which can be estimated by [9]:

$$Q = 16\pi^2 \frac{V}{\lambda^3} \frac{P_r}{P_T} \tag{3}$$

where V is the volume of the chamber, λ is the wavelength and P_r and P_T are the received and transmitted power respectively. If we divide the frequency by the Q then a bandwidth equivalence is obtained over which the resonant modes in a reverberation chamber are correlated. In the 2.4 GHz band there are 16 ZigBee channels each requiring 5 MHz of bandwidth. Therefore to avoid signal distortion a Q of below 480 would be required which, from Equation (1), would require P_r/P_T being less than -43.6 dB.

If we now consider an aircraft there are volumes within the structure which are multi-resonant and with relatively low loss. Whilst not flying there will be no vibration and an analogy could be drawn to the mode tuned reverberation chamber. Once flying the volumes within an aircraft will under go vibrations and distortions and these chambers could then be considered analogous to a mode stirred reverberation chamber. In terms of reliability of the wireless system whilst in service it would therefore be of considerable interest to see if it is possible to obtain a low packet error rate in an unloaded, or lightly loaded mode-tuned reverberation chamber and to then to study the effects of small changes in geometry via incremental steps of the stirrer. In this way some information can be obtained pertaining to the susceptibility of the system to vibrations.

In the tests reported here a commercial off the shelf ZigBee evaluation system was used, the Texas Instruments CC2520 development kit. Two evaluation boards were used, one set as the transmitter and the other as the receiver. The evaluation boards were placed into the reverberation chamber separated by approximately 3 m horizontally and raised 1 m off the floor. USB cables were run from the evaluation boards, through small apertures in the chamber wall to a computer. The Texas Instruments SmartRF Studio 7 software was used to control both evaluation boards and to evaluate the P_r/P_T ratio, the Packet Error Rate and the Received Signal Strength Indicator (RSSI). 2.4 GHz monopole antenna were connected to both the transmit and receive boards.

It should be noted that the RSSI measured with this equipment is the relative received signal strength when a packet has been successfully received and so is not the same as the power received by the antenna at the centre frequency of the channel.

3. RESULTS

Initially the chamber was unloaded and so had a very high Q. The first ZigBee channel was selected in the wireless system. The P_r/P_T ratio over one stirrer rotation was measured and seen to be between -26 dB and -28 dB, implying an effective Q factor in excess of 10,000. The stirrer was then stopped and stepped until a low PER was obtained.

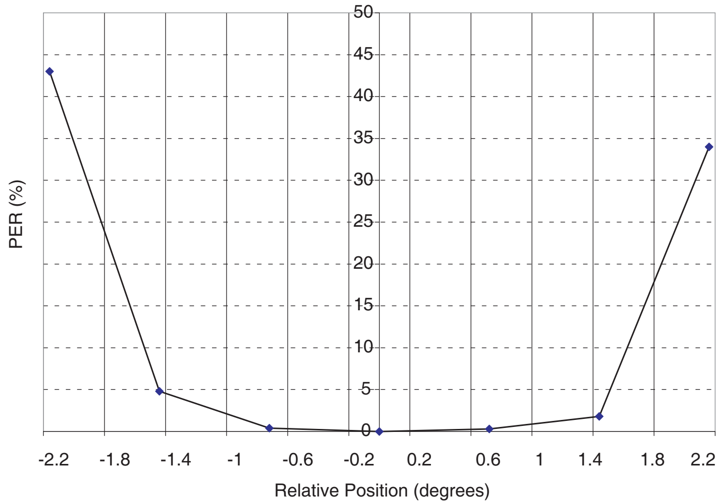

Figure 1. Variation in PER around 0% PER stirrer position.

By this incremental stepping a stirrer position was eventually found where 0% PER could be obtained. Fig. 1 shows the variation of PER around this position. It can be seen that even a small movement of the stirrer is enough to significantly reduce the PER. It should be noted, however, that the variation of PER around the 0% PER stirrer position depends on the chamber dimensions and the radiation wavelength.

The PER for all 16 channels of the 2.4 GHz Zigbee wireless system was now measured for the position where a 0% PER was obtained for channel 1. The only other channel where packets were successfully received was Channel 16, with a PER of 79.5%.

The losses of the chamber were now increased by opening doors and apertures, effectively adding radiation loss whilst the stirrer was maintained in the position where a 0% PER had been obtained for channel 1 previously. The results obtained are summarized in Table 1 where each channel has a 5 MHz modulation bandwidth, RSSI is the Received Signal Strength Indicator and the transmitted power is 0 dBm.

The results shown in Table 2 indicate that in only one channel (channel 9) was the receiver module unable to discover a transmitted signal. It can be seen that the PER in the other fifteen channels ranged from 0 to 93.7%. The RSSI is only measured for received signals and therefore is only an accurate measure of attenuation when the PER is close to 0%. It is interesting to note though that there is quite a large variation in RSSI, although for all cases it is less than −49 dBm.

Table 2. PER and RSSI for loaded chamber.

Channel	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
PER (%)	0	0	0.3	11.7	40.3	92.7	1	88.2	-	15.4	89.3	89.2	44.9	87.2	4	84.9
RSSI (dBm)	–49	–52	–50.7	–53.2	–56.3	–56	–51.1	–57.3	-	–55.1	–54.4	–54.3	–53.3	–51	–55.8	–50.5

The stirrer was now continuously rotated (mode stirred) at 500 steps per second and the P_r/P_T ratio at 2.4 GHz, over one stirrer rotation, was seen to be between -47 dB and -50 dB, much less than the -43.6 dB required for a 5 MHz bandwidth. Nevertheless it can be seen that there is still significant degradation of greater that 5 percent in 11 of the 16 channels across the 2.4 GHz ZigBee band. Since the bandwidth of the chamber is greater than 5 MHz in this case we believe that this degradation is primarily due to multipath effects, rather than inter-symbol interference. We believe that this result is consistent with the results of previous work reported in reference [5], which showed sharp variations in PER in a relatively low Q mode tuned chamber, for different stirrer positions.

4. DISCUSSION AND CONCLUSION

It has been found that ZigBee wireless communication is possible even in very low loss, high Q chambers, where the calculated equivalent bandwidth is much less than 5 MHz. This is an indication of the complexity of the electromagnetic field inside electrically large enclosures. The low PER only occurred for a single position of stirrer and was found to be extremely sensitive to small changes in the enclosures geometry. Although this variation in PER around the 0% PER position is very chamber dependent, since it depends on the dimensions and radiation wavelength, it does indicate that whilst being installed a wireless communication channel can be of good quality, even if the Q factor is high, it will be easily degraded by small perturbations of the enclosure.

Whilst a loaded chamber with a smaller Q factor had a bandwidth greater than the ZigBee modulation bandwidth, hence a low number of errors due to inter-symbol interference, it was seen that there was still a significant PER in most of the wireless channels. This is considered to be due to multipath fading and is consistent with the results obtained in reference [5].

These results lead us to conclude that successfully obtaining a low packet error rate using ZigBee in enclosed multi-resonant structures would require very careful analysis. We have shown that a low PER in one channel does not imply that this will be the case for all the channels and that consideration must be given to the vibration environment, electromagnetic losses (conductive, dielectric and radiative), and multipath fading if reliable communications is to be ensured.

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