EXPERIMENTAL INVESTIGATION OF WIRELESS TECHNOLOGIES FOR DATA ACQUISITION

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ABSTRACT

Now, more than ever, there is significant demand to reduce the weight of Flight Test Instrumentation (FTI) which in turn translates to cost savings. Moreover, there is the on-going requirement to improve the ease of installation, simplify wiring, and reduce power. Wireless technologies provide the ideal solution to overcome these issues by effectively eliminating the need for wiring which in turn reduces weight and simplifies the architecture. Wireless sensors are typically small, low-cost, low weight, and low-power devices that can be used to facilitate remote data acquisition in hard-to-reach and harsh locations in the aircraft. This paper discusses wireless sensor technologies and presents a prototype wireless sensor data acquisition module that was developed to investigate the feasibility of this technology for FTI data acquisition systems.

INTRODUCTION

The focus of this paper is on the use of wireless sensors for data acquisition in an FTI network. A Wireless Sensor Network (WSN) comprises spatially distributed autonomous sensors that cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion and so on. These wireless sensors transmit the acquired data to a wireless transceiver or controller in a data acquisition unit. From the data acquisition unit, the sensor data can be relayed from the Data Acquisition Unit (DAU) to the FTI network. Wireless sensors offer many advantages over their wired counterparts' namely no-wiring, low-cost, flexibility, mobility either to change the location of the sensor easily or for the sensor to mounted on a moving part, scalability to add more sensors as and when needed, and dynamic mesh and ad-hoc routing. Such properties make WSN solutions apt for data acquisition from sensors in hard to reach, difficult to wire, and mobile/dynamic environments.

Numerous Wireless Personal Area Networking (WPAN) technologies were analyzed including Bluetooth, Wireless LAN 802.11, and Zigbee 802.15.4 – Zigbee emerged as the most suitable technology for further investigation. Zigbee is a mature and standardized technology which is being pushed more into the industrial domain as can be seen by the development of industrial application-layer flavors of the Zigbee standard such as Zigbee-PRO and Wireless HART.

This paper describes the use cases and applications for which wireless technologies can be used for FTI and a prototype Zigbee WSN solution that enables the acquisition of analog signals and accelerometer data from wireless sensors. Each node in the WSN is equipped with a radio transceiver, a wireless network stack, a small microcontroller and an energy source, usually a battery, although there exist energy-harvesting sensors and Battery Lifetime Extensions (BLE) mechanisms within the Zigbee standard. The wireless sensors acquire measurements and wirelessly transmit them to a central coordination node or Personal Area Network (PAN) coordinator which is a Zigbee Fully-Functional Device (FFD), implemented on a standard Acra KAM-500 Data Acquisition user module. The data received by the PAN-coordinator is then stored in a Current Value Table (CVT) from which it is transmitted either as PCM or as IP packets to be transmitted across the wired-Ethernet DAS network. The paper will present findings on the feasibility and challenges presented using WSN in terms of throughput, latency, reliability, and contention with an increasing numbers of sensors. Based on this analysis, the paper will discuss directions for further investigation and prototype development.

USING WIRELESS FOR FTI AND DATA ACQUISITION

It is important to consider the use cases and applications where wireless technologies may be used to facilitate data acquisition and ensure that the right wireless technology is used to achieve this objective. The following use cases have been identified for FTI:

1. **Wireless Sensing**: wireless sensors gather measurements and transmit the acquired data to a wireless data acquisition user module that can then transmit the data to the wired Ethernet FTI network.
2. **Point-to-Point Wireless Data Acquisition**: A wireless Remote DAU (RDAU) acquires data from various sensors and busses; the acquired data is then transmitted wirelessly in a peer-to-peer manner to a receiving wireless DAU. This data is then forwarded into the wired Ethernet FTI network. For example, if an RDAU is located on a rotor or some moving part, it may not be possible to wire a data bus from the RDAU to the main FTI network, therefore wireless technologies may be used as a relay mechanism for the data acquired from the RDAU.
3. **Wireless Access Point (multiple wireless RDAU or multiple wireless receivers)**: Using a device such as an Access Point (AP), multiple wireless RDAU can associate with the AP and uplink their acquired data wirelessly to the AP. In this situation the AP acts as an aggregator-bridge to forward the wireless data to the wired FTI network. Conversely, the AP can be used as a bridge-distributor for situations where there may be multiple flight test engineers accessing and analysing the data in real-time in a flying ground station, for example.

4. **Wireless Bridge:** A standalone device that bridges between the wired Ethernet and wireless network. Unlike point-to-point wireless data acquisition where the wireless interface is part of the RDAU, by using bridges the RDAU is wired to the bridge which receives the Ethernet frames from the wired interface and transmits them wirelessly. The advantage of bridging is that the bridge can be located separate to the RDAU to get RF link performance. Moreover, the bridge does not necessarily have to be connected to an RDAU, it could be connected to any network node such as a switch or recorder enabling it to have wireless access.
5. **Wireless Data Mining and Real-time Analysis**: A wirelessly enabled PC connects to the on-board FTI network to mine the data recorded from the data acquisition system. It is envisioned that in this scenario, the aircraft has landed and the data is mined for post-flight analysis. In this case a flight test engineer can access the recorded data stored on the recorder. As previously mentioned, a wireless AP could be used for real-time analysis of the data. For example, if the aircraft is in an unmoving test rig, a wireless AP could be used for real-time analysis [1].
6. **Long range telemetry**: A long-range bi-directional wireless Ethernet link telemeters the data to the ground for analysis and is used for telecommand and control on the uplink [2].

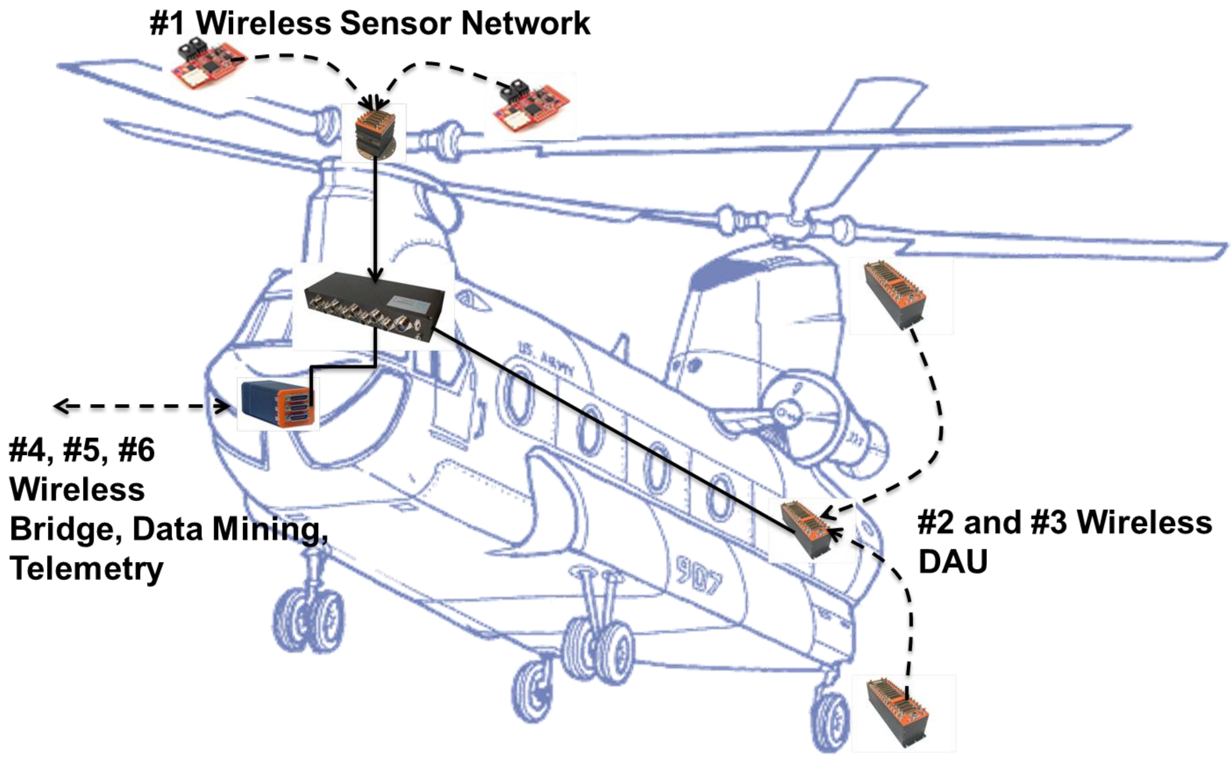

Figure 1: Wireless Use Cases for FTI Networks

WIRELESS TECHNOLOGIES

There are numerous standardized and proprietary wireless technologies that can be adopted to realize these use cases. Of the wireless standards studied, Table 1 presents the key properties and characteristics of the more promising technologies. These technologies were evaluated in terms of: standardization, maturity, bandwidth, range, security, and network join time. The latter is particularly interesting since the wireless link should be operational and recover in the case of link loss as quickly as possible.

	Zigbee **IEEE 802.15.4**	**Bluetooth** **IEEE 802.15.1**	**WLAN** **IEEE 802.11**
Data Rate	250kbps	v1.1 Standard 1Mbps; v2.0 and v2.1 EDR 3Mbps; v3.0 HS 24Mbps; v4.0 Low Rate 1Mbps	1-1Gbps
Standard	IEEE 802.15.4 Zigbee Alliance	IEEE 802.15.1 Bluetooth Special Interest Group (SIG)	IEEE 802.11
Maturity	802.15.4-2003 Zigbee 2007	v1.1 2002 v2.0 EDR, 2004 v2.1 EDR, 2007 v3.0 HS, 2009 v4.0 Low Rate 2010	802.11a (54Mbps) 1999 802.11b (11Mbps) 1999 802.11g (54Mbps) 2003 802.11n (100Mbps) 2008 .. more standards being defined
Battery	Low power modes and long life batteries	BT Low Energy v4.0, Designed for applications with frequent charging	YES Ultra low power 802.11n
Range (LOS)	75m typically, 1500m Zigbee-Pro	100m Standard 1m Low Energy v4.0	100m typically
Frequency	868 MHz (Europe) 900-928 MHz (NA), 2.4 GHz (worldwide)	2.4GHz	2.4GHz/5GHz
Access/ Modulation	DSSS	FHSS	DSSS/OFDM/MIMO
Access	CSMA/CA	FH-TDD	CSMA/CA
Security	AES-256	64 and 128 encryption	WEP/WPA
Maximum Number of Nodes	65536	8 Nodes/piconet, Larger topologies in scatternet	Unlimited - but ideally as few as possible due to contention effects
Network Join Time [3]	30msec	10sec	3-5sec
Topology	Ad-hoc, peer to peer, star, or mesh	Ad-hoc, very small networks Piconet/Scatternet	Ad-hoc, mesh or infrastructure

Table 1: Summary of Candidate Wireless Technology Characteristics

Bluetooth has many features that make it suitable for FTI for example: high bandwidths, low power operation, power saving modes and TDD for deterministic (quasi-deterministic behavior). It has a significant disadvantage in that it is a frequency hopping spread spectrum (FHSS) technology. Since RF emissions and frequency use is tightly controlled and regulated, Bluetooth was not considered a viable technology for the identified user cases.

WIRELESS SENSOR NETWORKS AND CHALLENGES FOR DATA ACQUISITION

Given that one of the primary motivators for using wireless technologies is to facilitate data acquisition from hard-to-wire and hard-to-install locations, all wireless technologies are challenged by the environment in which they operate. Briefly, these environmental factors include: reflection, diffraction, scattering, absorption, multi-path, Doppler effects, path loss and attenuation, and dispersion. In addition, there are a myriad of potential interference issues, for example, co-channel interference, interference from other RF emitting devices, atmospheric interference and so on. These are made even worse where there is mobility of the wireless device, for example if it is an RDAU or sensor located on a moving part since the environment is constantly changing.

Taking these environmental issues aside, both Zigbee and WLAN utilize CSMA/CA MAC access mechanism which is fraught with side-effects for data acquisition. Since, CSMA/CA operates on the principal of "fair-sharing" based on contention-based access to the RF bandwidth, this results in a time-varying throughput and per-packet delays which prevents any kind of deterministic behaviour when acquiring and transmitting data from an RDAU. As contention increases, i.e. the number of wirelessly enabled devices accessing the media, so too does the variation in throughput and jitter. Not only does contention cause problems for data acquisition, but it has been well documented that time synchronization using IEEE 1588 PTP protocol performs poorly over CSMA/CA technologies [4].

Having identified the use-cases and candidate technologies, the Wireless Sensor Network was selected for further investigation. A WSN comprises spatially distributed autonomous sensors that cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion and so on. Each sensor is typically equipped with a radio transceiver or other wireless communications device, a small microcontroller and an energy source, usually a battery. Since these sensors are typically battery operated they should have the ability to operate at low power and have the ability to harvest and store energy so that the life of the sensor can be extended and ensure that little or no intervention is needed with the sensors. These wireless sensors transmit the acquired data to a wireless transceiver or controller in a DAU where the data is aggregated for processing or is forwarded onwards to the wired FTI network. For a WSN to function in the context of data acquisition, the sensors must be able to withstand the harsh environmental and operating conditions. This means that the sensors should be able to operate autonomously and have the ability to cope with potential sensor failures without affecting the data acquisition or communication of the other sensors.

For WSN applications the IEEE 802.15.4 Zigbee was selected for further investigation for the following reasons:

- Standardized and mature technology, IEEE controlled standard that builds in interoperability with other IEEE standards, and backward-compatibility between the standard revisions.
- Low power consumption for extended battery support using the Battery Lifetime Extension (BLE) part of the standard and energy harvesting capabilities [5]
- Communications ranges are within scope and the range can be extended through ad hoc routing allowing for flexible topologies including star, mesh, or clusters.
- Low end-to-end latency and the possibility of optimizing the MAC access mechanism for determinism through the use of beaconed-enabled Guaranteed Time Slots (GTS).

ZIGBEE OVERVEIW

IEEE 802.15.4 technology is more commonly known as Zigbee, but is also known as Low-Rate Wireless Personal Area Networks (LR-WPAN). It was developed and designed with the objective of providing low power-usage thereby enabling longer life with smaller batteries while the mesh networking capabilities provides high reliability and larger range. Zigbee is a low-cost, low-power, wireless mesh networking proprietary standard published by the IEEE. The IEEE standard defines the PHY layer and MAC layer specification only, which means that the upper layers of the network stack can be tailored for specific applications. In addition to being an IEEE standard, the technology is supported by the Zigbee Alliance which is an association of companies working together to enable reliable, cost-effective, low-power, wirelessly networked, monitoring and control products based on an open global standard. The Zigbee Alliance ensures that such devices have a standards-based wireless platform optimized for the unique needs of remote monitoring and control applications where simplicity, reliability, low-cost and low-power are key performance requirements. The key features of Zigbee are

- **Data Rates:** can vary from 20 to 250 Kbps depending on the frequency used.
- **Frequency Band:** operates in the Industrial, Scientific and Medical (ISM) radio bands; 868 MHz in Europe @ 20kbps, 915 MHz in the USA and Australia @ 40kbps, and 2.4 GHz in most regions worldwide @ 250kbps.
- **Range**: Peer-to-peer range <75 m and up to 1500m with Zigbee-PRO.
- **Modulation:** Direct Sequence Spread Spectrum (DSSS) with OQPSK (transmits two bits per symbol is used in the 2.4 GHz band).

- **Packet Size:** IEEE802.15.4's standard packet size is 127Bytes. A maximum frame overhead of 25Bytes leaves 102Bytes at the MAC layer.
- **Addressing:** IEEE 802.15.4 devices may use either of IEEE 64 bit extended addresses or (after an association event), or 16 bit addresses that are unique within a PAN. The PAN coordinator assigns a 16bit identifier for all communications. There is also a PAN-ID for a group of physically collocated IEEE802.15.4 devices – essentially this is a subnet.
- **Reliability:** Acknowledgement for a packet is optional and whether support for ACKs is enabled is flagged in the data packet.
- **Fast access times** and low latency support using GTS
- **Number of Nodes**: maximum of 65536
- **Routing and Topologies**: Star, Mesh, and Cluster with infrastructure and adhoc routing support.
- **Power:** Operate at lower power than Bluetooth. IEEE 802.15.4 supports a "Battery Life Extension" (BLE) mode, in which the CSMA/CA back-off exponent is limited to the range 0-2. This greatly reduces receiver duty cycle in low offered traffic applications.
- **Energy Harvesting Capabilities:** Included as part of the Green Power specification released by the Zigbee Alliance in 2009.
- **Security**: Security enabled. An optional but highly recommended security feature at the link layer using AES-CCM-128. This extra overhead reduces the payload carrying capability to 81Bytes.
- **Version compatibility**: Zigbee 2007 is fully backward compatible with Zigbee 2006 devices: A Zigbee 2007 device may join and operate on a Zigbee 2006 network and vice versa. Due to differences in routing options, Zigbee Pro devices must become non-routing Zigbee End-Devices (ZEDs) on a Zigbee 2006 or Zigbee 2007 network, the same as Zigbee 2006 or Zigbee 2007 devices must become ZEDs on a Zigbee Pro network.

Within IEEE 802.15.4 there are two modes of network operation, namely beacon-enabled and non beacon-enabled. It is the role of the PAN coordinator to determine the network type. **Non-beacon-enabled** networks use unslotted CSMA/CA and the PAN coordinator will not send any beacons. The motivation for non-beacon enabled networks is to conserve power in the PAN coordinator allowing it to sleep and save power. In this vain, devices receive continuously, while others only transmit when an external stimulus is detected. However, this form of power consumption is asymmetrical i.e. some devices are always active, while others spend most of their time in sleep mode. A **beacon-enabled** network uses slotted CSMA/CA and the PAN coordinator sends periodic beacons. Router FFDs transmit periodic beacons to confirm their presence to other network nodes and this allows for nodes to sleep between beacons, thus lowering their duty cycle and extending their battery life. Beaconed networks are more power efficient since the time the radio is on can be minimized thereby reducing power consumption i.e. nodes only need to be active while a beacon is being transmitted. Another advantage of beaconed networks is the use of GTS to meet the requirements of low latency for sensor data acquisition and transmission.

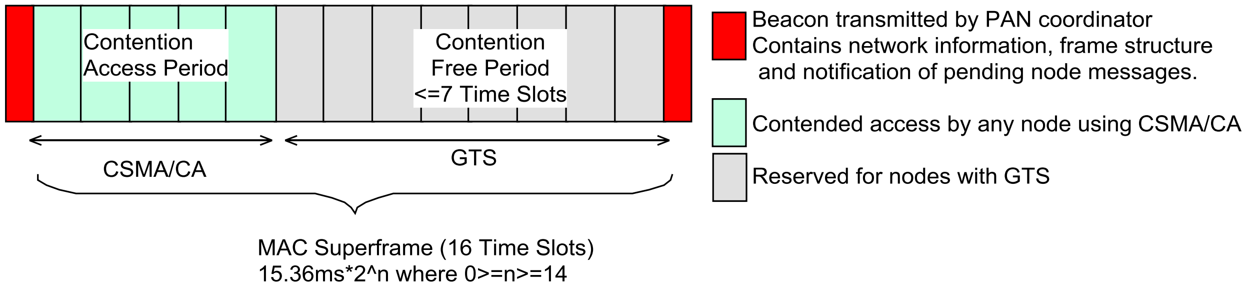

Figure 2: Beacon-Enabled ZigBee Superframe

The beacon intervals delineate superframes. Typically the duration between two successive beacons is the superframe duration. A MAC superframe is divided into 16 slots and consists of a **CAP** (Contention Access Period) followed by **CFP** (Contention Free Period) as shown in Figure 2. The CAP starts after the beacon signal and must end before the CFP. During the CAP nodes contend using CSMA/CA to gain access to transmit their data. The CFP consists of GTS but is restricted to use up to 7 of the 16 slots that make up the superframe and a GTS may occupy more than one slot. All information about the GTS for various nodes during the CFP is communicated by the PAN coordinator in the beacon signal. All GTS transmissions must be completed before the next beacon.

ZIGBEE PROTOTYPE

The WSI/101 is a Zigbee IEEE 802.15.4-2006 PAN coordinator Acra KAM-500 module with a top block mounted 1" stub SMA-type antenna. The PAN coordinator is configured with a PAN ID and set to operate on a specific channel. Moreover, the MAC can be configured with a beacon interval and have ACK frames enabled or disabled. The WSI/101 is a parser module that can acquire data from up to 64 sensors. The systems configuration for the WSI/101 and associated sensors is shown in Figure 3. The WSI/101 is programmed by mapping the id of the sensor to a corresponding parser slot. The WSI stores the entire data frame from the sensor in the corresponding parser slot and ignores any "unknown" sensors. During the experimental investigation, the WSI/101 supported only a star topology, mesh and adhoc routing between the sensors was not used since this introduces uncertainties and non-deterministic behavior which complicates analysis.

The wireless sensors used during the experimental investigation were the industrial grade Zolerta Z1 wireless sensors. The Z1 sensors are powered by 2xAA batteries (or AAA or button cell). They have a standard IEEE 802.15.4 interface from which data is transmitted from the built-in temperature and accelerometer sensors. When the Z1 sensors are powered on, they scan the RF channels to find a PAN coordinator that they can associate with. If the sensor does not detect a PAN coordinator, they go to sleep for 2 seconds and on wakeup, they repeat the scan process. When the sensor has detected a PAN coordinator it will attempt to associate with the coordinator by sending an association request. Association request commands received by the WSI/101 from defined sensors are accepted by responding with an association response command. Associated requests from “unknown” sensors are rejected.

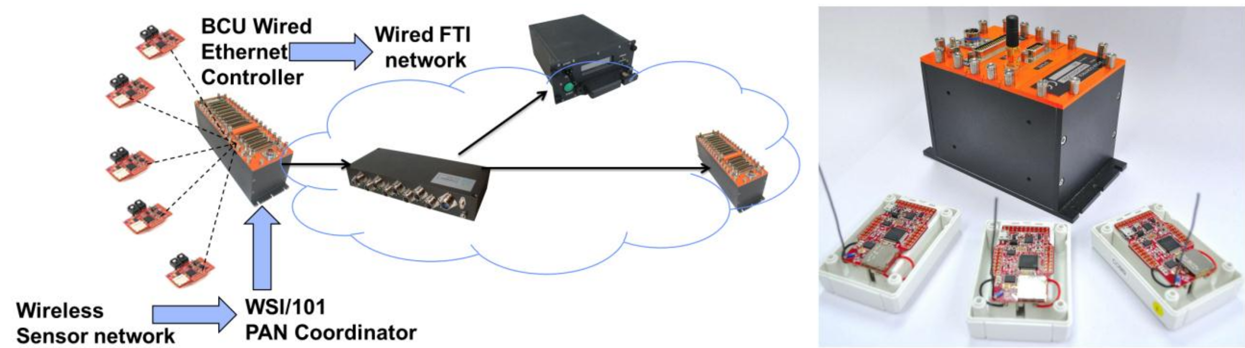

Figure 3: WSN Configuration for Data Acquisition using WSI/101 PAN Coordinator User Module

The WSI/101 supports remote node configuration over air. Once associated with the WSI/101, the first packet transmitted by the sensor is a configuration request. The configuration request is issued by setting a flag in the data frame. When the WSI/101 detects this flag it responds with a data frame that contains the configuration data for that sensor. Once the sensor has received the configuration data, it begins to transmit data packets. If the sensor has not received the configuration data from the WSI/101 within 1second, it will retry up to 3 times to request the configuration.

RESULTS

Zigbee has a maximum over-the-air capacity of 250kbps which constrains the usefulness of Zigbee for data acquisition in terms of the number of sensors that can be supported on a given channel and also the amount data that can be transmitted by each sensor. To investigate the number of sensors that can be supported by a single WSI/101 module operating on a given channel over time, more and more sensors were associated with the coordinator. To improve the reliability of the system, the WSI/101 was set to operate in ACK mode. The Acra KAM-500 system monitored the quality and reliability of the received data from the sensors by checking sequence numbers and error registers of the WSI/101 parser slots. Each sensor was configured to transmit 40 data frames per second with 97Bytes of data in each frame resulting in an offered data rate of approximately 32kbps per sensor. It was found that with this configuration, only 4 sensors could be reliably supported resulting in a combined reliable aggregate data rate of 130kbps. This low data rate is to be expected due to the nature of the CSMA access mechanism by the sensors to contend for access to transmit. This contention results in frequent backoff of the sensor before transmitting which manifests as “wasted” time waiting and (ironically) increased unused bandwidth. To support more sensors reliably, additional WSI/101 modules can be used in the DAU, each operating at a different non-overlapping channel. In subsequent investigation, the throughput capability of Zigbee was investigated. The throughput is affected by a number of factors: the packets per second; the size of the packets being transmitted; and the number of sensors contending for access. In addition, Zigbee can be configured for reliability whereby there MAC-ACKs may be used.

With a single sensor associated with the WSI/101, 500Pps minimum sized packets of 40Bytes can be transmitted reliably (8kbps). As the number of sensors is increased to 8, a maximum of 12Pps (0.192kbps) can be transmitted per sensor. This translates to a total packet rate of 96Pps (1.56kbps) aggregated over all 8 sensors. This exponential decay in achievable packet transmission rate from the sensors is a direct result of the CSMA contention access mechanism. Similarly if larger packets are used, there is a more efficient use of the bandwidth since fewer packets are required to transmit the same offered load and less bandwidth is consumed by packet header overhead. However, larger packets require more bandwidth per packet. This effect can be seen by comparing the black full and dashed lines in Figure 4. As to the effect of ACKs on the throughput of the system – for every data frame transmitted by the sensor and received by the WSI/101, an ACK frame is transmitted by the WSI/101. The use of ACKs improves the reliability of the system. However as expected, using ACKs reduces the throughput capacity of Zigbee since not only does each data frame use bandwidth, but so too do the ACK frames. In Figure 4, it can be seen that the full black line is the throughput without using ACKs, while the full grey line represents the throughput of the system using ACKs. With a single sensor transmitting minimum sized packets the additional bandwidth required for the ACKs 2.7kbps. Moreover, not only do ACKs consume bandwidth but they increase the contention levels. As the number of sensors is increased, using minimum sized packets and no ACK 0.192kbps is transmitted per sensor (or 1.56kbps aggregated over all 8 sensors) whereas using ACKs 0.16kbps is transmitted per sensor (1.28kbps aggregated over the 8 sensors).

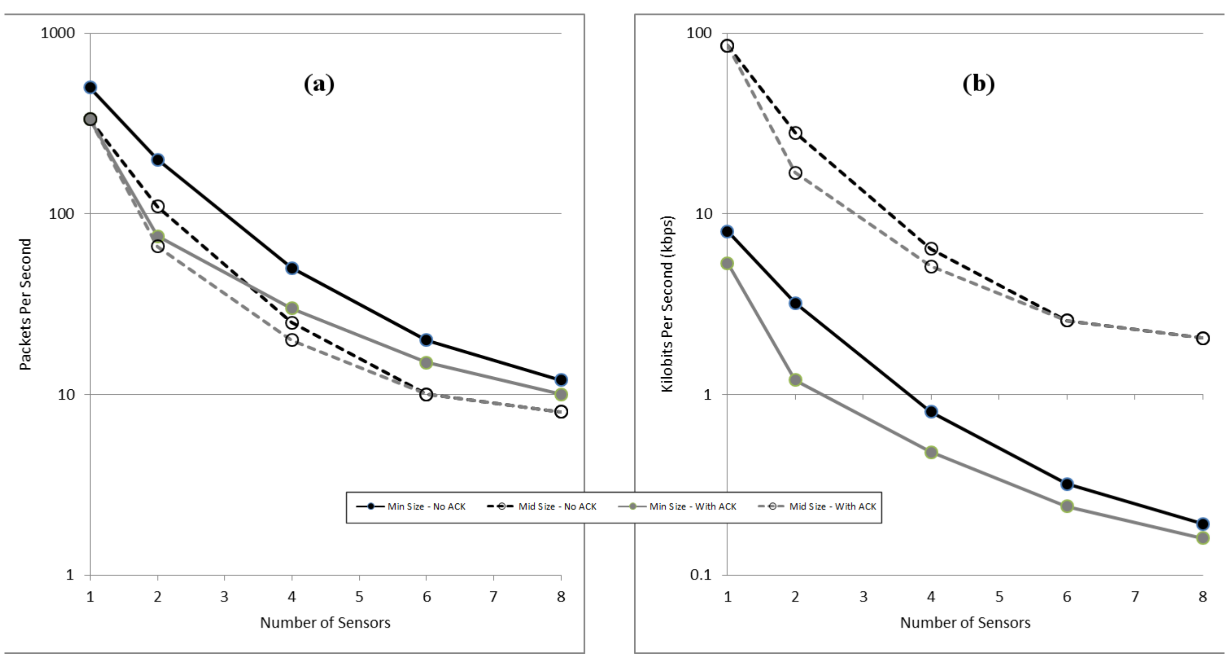

Figure 4: (a) No. sensors –vs- Packet Transmission Rates (b) No. Sensors –vs- Throughput

It is clear that there is a significant limitation in terms of throughput capabilities of Zigbee sensors for data acquisition systems. Only where the sensors have low sampling rates and low packet transmission rates would Zigbee be able to provide the necessary throughput and reliability. Similar results have been found for the use of WLAN technology for real-time data acquisition and this is due primarily to the CSMA/CA access mechanism and contention effects [6,7].

CONCLUSIONS

The benefits of using wireless technologies for data acquisition are clear in terms of reducing wiring, and facilitating ease-of-install and wire. But wireless technologies pose many challenges for the reliability and determinism of transmitting the acquired data. This paper focused on the use of Zigbee for wireless sensor networks (WSN) which could conceivably be the installation of remote wireless sensors on remote or moving parts of the aircraft. Even in the best-case Zigbee has a maximum bandwidth capacity of 250kbps which severely restricts the amount of data that can be acquired and transmitted. Furthermore, from investigations it has been shown, as expected due to the CSMA/CA access mechanism, that the throughput of a WSN exponentially decays with the number of sensors transmitting to the PAN coordinator WSI/101 module. One mechanism to increase the throughput and minimise the contention effects is to use multiple PAN coordinator WSI/101 modules operating a different non-overlapping channels, however having multiple antennae of WSI/101 modules in close proximity will introduce interference issues. To improve the determinism of Zigbee, industrial variants of Zigbee include ZigBee-Pro, ISA-100, and Wireless HART. Each of these variants uses the same underlying IEEE 802.15.4 RF link but have tailored the upper layers of the stack to meet the requirements of specialized applications.

More generally, there are a number of steps that can be used to improve the performance of both WLAN and Zigbee wireless technologies for data acquisition. Methods to overcome the issues presented by CSMA/CA MAC access mechanism include reducing the levels of contention by limiting the number of wireless devices attempting to transmit on the shared channel, using multiple non-overlapping channels to increase the throughput of the system and distributing the number of wireless devices across multiple channels. This would make effective use of the RF bandwidth by optimizing packets i.e. transmitting larger packets will require fewer packets transmitted and therefore fewer RF accesses and reduces contention than transmitting more smaller packets. The challenge of time synchronization is the subject of another investigation and was not addressed in this paper; however there are QoS mechanisms that can be employed. For example, using Zigbee WSN applications, the use of GTS can be used to improve the determinism and latency of acquisition from the sensors. For WLAN, the IEEE 802.11e standard provisions for the prioritization of data packets through the use of multiple queues in the AP similar to DiffServ [8]. In this way, IEEE 1588 time synchronization could be assigned to a high priority queue which would mean that there is a reduced queuing delay for these packets which can in turn reduces the channel access delays and asymmetry.

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