Jurnal Teknologi

Full paper

A Survey On Wireless Based Industrial Tomography System

Goh Chiew Loon[a*], Ruzairi Abdul Rahim[a], Mohd Zikrillah Zawahir[a], Mohd Fahajumi Jumaah[a]

[a]*Process Tomography & Instrumentation Engineering Research Group (Protom-i), Infocomm Research Alliance, Control and Mechatronic Engineering Department, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*

*Corresponding author: helenclgoh@yahoo.com

Article history

Received : 1 April 2013
Received in revised form :
30 May 2013
Accepted : 5 June 2013

Graphical abstract

$P_R = P_T [G_T G_R \lambda^2 /((4\pi)^2 d^2)]$
Equation 1

Abstract

This paper presented a survey on wireless based industrial tomography system, and to review design challenges in the field of embedded wireless solutions. Focuses are on presenting recent researches in wireless based industrial tomography system, and providing the wireless protocols supported by the current embedded technologies. We also explain the influences of wireless characteristics such as RF spectrum usage, Link budget, RF agility, antenna and power consumptions in the performance of the designed wireless system. In this paper, we intend to introduce a set of practical considerations for embedded wireless tomography system design.

Keywords: Industrial tomography; embedded wireless; rf spectrum usage; link budget; wifi; ZigBee; bluetooth

1.0 INTRODUCTION

Wireless technologies have become fast and power efficient enough that the adoption of wireless communications is more widespread than ever before. Embedded wireless systems are the combination of an embedded process with a wireless interface for communicating between each node. From Bluetooth headsets to industrial process automation, this motivates electronics designers to look toward wireless solutions for embedded wireless control and connectivity as a way to differentiate and improve their products. The development of efficient and flexible wireless technology has created a wide variety of potentially new wireless systems. Wired solutions are not practical in this kind of harsh industrial environment [1]. Thus, in this paper, we focus on the survey on the wireless approach in Industrial Tomography System (IPS) and provide design considerations in embedded wireless system.

Tomography is an interdisciplinary field which aims to obtain cross-sectional images of an object, originally applying for medical analysis. Industrial Tomography System is a computerized system that can provide cross-sectional images of an investigated pipeline in industrial process. There are many methods of performing process tomography, major methods widely being researched are Electrical Capacitance Tomography (ECT), Electrical Impedance Tomography (EIT), Optical Tomography, Nuclear Magnetic Resonance Tomography (NMR), Radio Frequency (RF) Tomography, Electrode Resistance Tomography (ERT) and Ultrasonic Tomography. Agile Sensing Systems for tomography had been introduced in year 2011. The achievement of measurement agility is usually accompanied by two further critical features that are characteristic of agile tomography systems. First is the bespoke engineering for sensor access to the measurement environment, ensuring physical process compliance of the sensor system. The second is the sophisticated electronics to achieve sensitivity to the desired measurement, to have high signal-to-noise ratio (SNR) for useful image reconstruction [2]. The tomography system designer is faced with a major architectural decision in choosing between hard-field and soft-field modalities. Hard-field sensing methods refer to the sensing contribution to the actual measurements only depends on the process medium inside the volume defined by the source and detector [3,56]. The simplest example is X-ray tomography, where the measurements based on the straight-line path through the subject, such as the measurements will not influenced by the environment outside the subject volume. For the latter, the soft-filed case arises where any change of measurement at any position in the subject can influence the measurement obtained on any detector in response to a given excitation because of the fringe effects related to electrical and electromagnetic fields, irrespective of excitation and detection geometry. The simplest example is ECT, which in ECT system, a change in permittivity anywhere in the subject will modify the electric field lines everywhere in the subject, and thus influence measurements for all geometrical configurations of voltage excitation/current detection [4].

This paper makes the following contributions. In section 2, we review on recent researches in the field of industrial tomography system based on wireless technologies. In section 3, we provide a contemporary look at the current RF technologies implementing in embedded wireless solution. Here, we identify the various wireless characteristics that not to be overlooked when designing the embedded wireless solutions, in which we illustrate how these considerations affecting the RF range performance in embedded wireless system. We also discuss about energy source consideration in maximizing the battery life while designing embedded wireless system. Finally, this paper is concluded in section 4.

■2.0 INDUSTRIAL TOMOGRAPHY RECENT RESARCHES WITH WIRELESS APPROACH

This section presents most relevant applications in recent industrial tomography researches. In general, wireless approach can be categorized into two areas of technologies: wireless communication and radio Frequency (RF) tomography.

Wireless communication is referred to communication protocol between sensor front-end design and image application. It is equivalent important to drive an industrial tomography system to a success. A success implemented communication protocol makes hardware system a real time system. Authors in [5] implemented an industrial ultrasonic tomography for monitoring water and oil flow, a commercial data acquisition card which using computer compatible PCI bus had been deployed to master the front-end electronic system, and acquiring data into PC system. Most of the researches had implemented tomography system in the form of wired based data acquisition, which leads to the usage of serial bus RS232 or USB bus, was the communication link to PC for further data analysis in image reconstruction [6] [7] and [8].

In year 2005, Infratography was introduced. Infratography describes heterogeneous wired and wireless networks, augmented by smart cooperating agents in the entire network, to enable a variety of distributed monitoring and control functions in industrial system via wireless sensor network [9]. WSN technology provides a viable platform for distributing a large number of sensing elements within a wide area. In order to automatically detect the cardinal (highest or lowest) value in a wide area distribution, the developed system in [10] periodically sent a single directed alert message to a monitoring point. A simple message can notify the network of an interest in a threshold level, perhaps a gas concentration value, and again nodes having this level can alert this status.

Concurrently the progress of Infratography, a new technique called "Ad Hoc Wireless Sensor Tomography" had been introduced. The technique was inspired by need of elimination of substantial modification to process vessels with the wiring challenges [11]. The technique involved ad hoc wireless sensor networks that were hosted in a process vessel, and was deployed in ERT system [12], which in contrast to conventional arrangement of electrodes was at the outer layer of industrial pipeline; their unconventional arrangements of electrodes were free to move with the flow in the vessel. This wireless sensor technique had improved tomographic results, from the increased number of measurements, and to explore optimum techniques to reconstruct 3D images. Using same concept of ad hoc sensors, author in [13] deployed wireless communication and derived 3D tomographic imaging. The difference with earlier work is besides ad hoc wireless sensors located inside the pipeline, there were also conventional wall-mounted electrodes. The ad hoc wireless sensors giving the mobility to assume any location inside a process vessel, properties of interest such as temperature, pressure, pH level and conductivity can be measured. Each the ad hoc sensors in the vessel system were equipped with the embedded wireless communication system, which consisted of a microcontroller, four RF antennas, and an 868MHz RF transceiver. The wireless communication transmitted data from sensors to PC, the base station for further analysis. Disadvantage of this system is that although the ad hoc sensors were designed to be as small as possible, it is still intruded on the process initially. However, Renee's research is a successful wireless set up in ERT tomography system. In year 2011, Mark G. and York Trevor A, advanced the ad hoc wireless sensor concept into ultrasonic tomography system [14]. The research team worked based on consideration on the two industrial scenarios, conducting and non-conducting media respectively. In non-conducting vessel, RF propagation is a natural candidate technology. However, when the media are conductive, RF is inappropriate and acoustic or ultrasonic techniques emerge as an attractive solution. The team concentrated on the challenge to determine the ad hoc wireless sensors' position, using small, low power and low cost ultrasonic transducers driven by a low voltage, 10 Vpk-pk. Their software modelling was able to provide strategic location of four ultrasonic transmitters that to be mounted around the periphery of the designed ad hoc pill. However, future works still need to be explored on the optimization of receiver locations at the outer pipeline of the process vessel with interest in how different modelling copes with the measurement errors.

Lately, in year 2012, authors in [15] had successfully developed a RF based wireless digital data transmission module (WDDTM) in electrode switching of an EIT system. An analogue multiplexers based electrode switching module (ESM) was developed with analogue multiplexers and switched with parallel digital data transmitted by a wireless transmitter/ receiver (Tx/Rx) module working with radio frequency technology. The transmitter/receiver module developed was properly interfaced with the personal computer (PC) and practical phantoms through the ESM and USB based DAQ system respectively. Comparisons had been analysed based on wired and wireless system, and results showed that, the boundary potential profiles of obtained with or without inhomogeneity were of similar fashion both for opposite current injection with wired instrumentation and common ground current injection methods using WDDTM.

The rapidly technology progress in wireless field has attracted considerable Radio Frequency (RF) tomography research efforts since the early 2000s. RF tomography is a process of inferring information about an environment by capturing and analysing RF signals transmitted between nodes in a wireless sensor network. In 2007, tomographic imaging of room-sized spaces using the propagation properties of 2.4GHz, IEEE 802.15.4 Direct Sequence Spread Spectrum (DSSS) radio waves had been demonstrated in [16]. Instead of analysing data located in the payload of packets, the network itself was used as a dynamic sensor to collect data. By using the received signal strength indication (RSSI) value of packets being received in the network with a known physical configuration, deflections in the RSSI value could indicate a physical obstruction in the network. Field test with phantom objects of known location, size, and material had been conducted, and results showed that the wireless application is feasible throughout an 802.15.4 network. In year 2009, Compressed Radio Frequency Tomography had been introduced; it is an approach that combines RF tomography and compressed sensing for monitoring in a wireless sensor network [17]. Information is processed based on RSSI measurements together with the basic analysis of the data located in the payload of the network packets. Under certain assumptions, compressed sensing techniques can accurately infer environment characteristics. This research demonstrated experiments with simulated and real data in proposed models to show the capabilities of their approach in both centralized and decentralized scenarios.

In year 2010, there was a research breakthrough with idea of wireless tomography, which is a new initiative to bring together two areas of technologies: wireless communication and radio frequency tomography [18]. The research team suggested a self-coherent wireless tomography, by combining wireless communication and remote sensing. This novel approach has two steps. First, the phase retrieval was achieved using amplitude only data that were obtained through wireless sensors. Phase reconstruction means reconstructing the scattered field from the information in the incident field and squared amplitude of the total filed. Second, standard radio tomographic imaging algorithms were used. Conclusion from the results of the research showing that the architecture of a phase reconstruction algorithm, to retrieve the phase of a communications signal, combined with time reversal imaging was promising. In the phase two of the system design, the team have improved the wireless tomography system by applying machine learning and waveform diversity. Since the size of sample space in phase reconstruction is large, machine learning can be applied to reduce the dimensionality of dimensions - thus reducing the effect of measurement error induced by Commercial, Off-The-Shelf (COTS) communication components [19]. The random errors introduced by the COTS components tend to be infinite, compared with the finite dimensions. Machine learning has been applied before the phase reconstruction step and the coherent tomographic processing step. The new three-step approach worked much better than the traditional two-step phase reconstruction approach. It has been demonstrated that the proposed machine learning and waveform diversity techniques improves the reconstructed scattering strength. In the phase three of wireless tomography system, the same research team further proposed a compressed sensing (CS) based UWB channel recovery method considering pulse distortion. The concept has been demonstrated through simulations with the results of sampling rate is reduced as low as 2 Gsps, compared with the Nyquist rate of 50 Gsps [20]. Previous literatures on wireless tomography rarely addressed the noise issue. Accurate phase information is hard to obtain using wireless communication devices, especially in the presence of noise. In early year 2013, researches in [21] dealt with wireless tomography in noisy environment for real-world applications, by proposing a novel hybrid system for wireless tomography. The fundamental issue regarding the retrieving of accurate phase information from noisy environment when wireless devices were used was addressed in their research. The team highlighted in their mathematical simulation the three key steps of working wireless tomography in noisy environment; they were noise reduction using kernel PCA, modification of standard phase reconstruction and the corresponding imaging algorithm in filtering noise. Improvement to the wireless tomography research had been continued, to integrate the simulation results into the set-up of the hybrid system to demonstrate the real-world wireless tomography system [22].

Asides all above mentioned researches, there is an interesting approach in wireless based industrial tomography system, which is the idea of using Field Programmable Gate Arrays (FPGA) [23] to reconfigure wireless stand-alone platform for ECT. The developed system is stand-alone without data transferring and processing using computer. New hardware architecture to integrate WSN technology and the FPGA technology instead of the personal computer as the hardware platform had been proposed to realize ECT system in achieving superior performance in terms of speed and design compactness compared to PC based industrial tomography system. The significant contribution of the research was wireless transmission of the ECT measured data to the FPGA processing unit, and tomographic results displaying onto LCD instead of computer monitor that making the ECT system more viable in the industrial boundary scale.

3.0 DESIGN CONSIDERATION IN WIRELESS SOLUTION

Surveying from the recent researches in area of industrial tomography, it is found that wireless communication protocol is less attended as crucial experiment as focuses are more on the sensors improvement, noise elimination, and image algorithms. As we are in the midst of a wireless revolution, wireless technology shall be a potential element in industrial tomography that enable a major saving in system instalment and maintenance cost. Embedded wireless development environment is different from that of PCs. Embedded platform offer fewer application programming interfaces (APIs) than PCs do, and the APIs in some embedded platforms will feel unfamiliar to those who have programmed only PCs [24]. PC APIs can reduce the learning curve and make it easier to port software, but programmers need to be aware that not all PC functionality is supported in embedded wireless systems. Although development tools for embedded systems continue to improve, they typically do not have all the features of tools designed for a PC host. The development support situation is changing rapidly as the wireless embedded systems and applications evolve, but for now embedded wireless developers are faced with a challenging environment as they turn their efforts to creating wireless applications. Embedded wireless designer immediately run into barriers like power, reliability, range and the basic problem that RF is challenging to design with.

Most of the chip sets for implementing the communications protocols and RF links for wireless systems were developed for the personal-computer market, in the other words, many chip sets utilize the PCI bus as the wireless interface for their host-processor connection [25]. Embedded systems, on the other hand, use a wide range of low- and mid-performance processors, which these processors generally don't offer a PCI-bus interface. This situation leaves embedded-systems designers with a dilemma: The wireless chip sets that they need can't directly connect to the processors that they want to use. FPGA can be used to serve as the bridge device to adapt to PCI buses in computers. The need for wireless connectivity in embedded systems is growing which leads to the rapidly evolvement of wireless embedded modules. As this cast market opens up, today, there are legion of choices exists for implementing wireless data connections from embedded system to computer, not only via PCI bus interface, also through variety of communication interfaces such as USB, serial port, Bluetooth and Wi-Fi to the core processor of the embedded system. These off-the-shelf wireless evaluation modules help designers in overall in getting their designs with shorter time to market. Instead of spending significant time and money developing wireless specific hardware and protocol stack, designers can focus more on the core competence in sensor hardware and product application.

3.1 RF Spectrum Usages

The first parameter to think of in embedded wireless design is RF spectrum usage. Due to the nature of RF waves, the lower the RF frequency, the larger the wavelength is and thus the less prone to absorption by typical manufacturing materials such as liquids and reinforced concrete [26]. However, RF spectrum and its usage is a highly, governmentally regulated area of wireless communications to minimize interference with other wireless communications technologies. Only a few areas of the spectrum are reserved either locally or internationally for unlicensed use for these forms of communications, these are known as the Industrial, Scientific and Medical (ISM) band. Within this band, the predominant frequency that’s accepted and used are the 2.4-GHz portion of the ISM band and the proprietary Sub 1GHz RF. The 2.4-GHz ISM band is available for license-free operation in most countries, thus it allows same solution for all market without software/hardware alterations. The higher frequency RF, 2.4-GHz range makes the need of more compact antenna design as compared to sub 1 GHz ISM band, this allows more separate channels with higher data rates transmission. However, the cons of 2.4 GHz ISM band comparing to proprietary sub 1 GHz is, with the same current consumption, it has a shorter transmission range, and more possible interferers are present in the same band. Proprietary (non-standard, unlicensed based) Sub 1 GHz ISM bands are not world-wide, limitations vary a lot from region to region thus getting a full overview on design is not a simple task. This leads to no worldwide solution is possible, since different bands are used in different regions, a custom embedded wireless solution has to be designed for each the region.

Surveying in current market, the common wireless ISM standards that implementing in embedded wireless systems are Local Area Network (LAN) IEEE 802.11, also known as Wireless Fidelity (WiFi), Personal Area Network (PAN) IEEE 802.15 and proprietary Sub 1 GHz ISM. The IEEE 802.11 protocol was introduced in 1997, and along the years, this protocol had been derived into few set of different physical layers, to have better supporting to the evolvement of the RF technologies. The derivation of the WiFi are referred by an identification letter, up to today, there are 802.11a, 802.11b, 802.11b/g, 802.11g and 802.11n [27]. High Data rates in PC based WiFi solution ranges up to 600 Mpbs depending on the interference and the distance between sender and receiver. Within a short decade, the data rate of 802.11 family products have evolved at an amazing pace, from 1 Mb/s with the first generation of 802.11 products, to 11 Mb/s with 11 b, to 54 Mb/s with 11a/g, to up to 600 Mb/s with in MIMO 802.11n products [28]. It is about 30 times faster over this period, roughly matching Moore's law advances in computing speed. There is also an on-going effort to migrate indoor LAN and PAN networks toward less congested higher frequency unlicensed spectrum bands such as 60 GHz. There are significant propagation-related differences and challenges between the 60-GHz band and the lower frequency unlicensed WiFi bands at 2.4 and 5.0 GHz. Several standardization bodies have been working on the 60-GHz PHY and MAC protocols approaching 1Gbps service rate. The 60-GHz technology is expected to mature during the next three to five years, and this future technology is expected to provide an important option for high-speed indoor connectivity associated with applications [29].

Among all the variety of embedded wireless networking protocols, only WiFi integrates with the protocol designed for exchanging data with Internet access to devices. The free TCP/IP (Internet Protocol Suite) stacks in the WiFi protocol allows internet access by network application. Although popular in commercial applications such as wireless LAN within homes, business and stores, Wi-Fi has gain limited traction in remote monitoring and control due to its limited transmission range and security concerns [30].

Covers under PAN IEEE 802.15 network are IEEE 802.15.1 and IEEE 802.15.4. IEEE802.15.1 is also known as Bluetooth. Bluetooth allows for data rates of up to 1 Mbps over distances of 5 - 10m (Bluetooth Class II) to 100m (Bluetooth Class I) in the 2.45-GHz band. When a Bluetooth device is in power down mode, it would take slightly long time (about 3 sec) to wake up and respond [31]. Bluetooth played an interesting role in the past of PAN: it offers a good compromise between data rate (about 1 Mbps) and range (about 10 m or 100m with lower data rates). However, this trade-off seems to be its main limit: WiFi seems to be preferred for higher data rates and Zigbee for lower consumptions and longer battery life. IEEE 802.15.4 is a protocol standardizes ultra-low complexity, ultra-low cost, ultra-low power consumption, and low data rate wireless connectivity among inexpensive devices. It is commonly referred as ZigBee. A ZigBee compliant wireless device is expected to transmit 10-75 meters, depending on the RF environment and the power output consumption required for a given application, and will operate in the unlicensed RF worldwide (2.4GHz global, 915MHz Americas or 868 MHz Europe). The data rate for 802.15.4 varies depending on the device operating frequency. For the updated version announced in year 2006, IEEE 802.15.4a, for the 2.4GHz band, the raw data rate is 250kbps, 915MHz data rate is 40/250 kbps, and 868MHz is 20/100/250 kpbs [32]. ZigBee supports very fast wake up time. When ZigBee node is powered down, the wake up time to receive a wireless packet is in around 15msec [31]. Aside ZigBee, there are several data communications standards use the IEEE 802.15.4 as a base of lower protocol layers. They are 6LoWPLAN, and WirelessHART. Table 3.1 summaries the general specifications in each the embedded wireless standard protocol. Despite the plethora of wireless options, major considerations to be attended to during selection of the suitable wireless embedded module is the RF bandwidth, range, data transmission rate power consumption and also cost.

Several varieties of Wi-Fi, Bluetooth, ZigBee, and Sub 1GHz for implementing a wireless link can be chosen from off-the-shelf wireless modules. Referring to technical specifications in [30] and [33 - 48], Table 3.2 provides summary of some up-to date suggestions on recent wireless solution offering by wireless chipset vendors.

Table 3.1 General specifications in standard ISM band

Wireless Standard	802.15.4 ZigBee	802.11 WiFi	802.15.1Bluetooth
Data Rate	20, 40, and 250 kbps	11 & 54 Mbps	1 Mbps
Estimated Range	10-100 meters	50-100 meters	10 meters
Networking Topology	Ad-hoc, peer to peer, star, or mesh	Point to hub	Ad-hoc, very small networks
Operating Frequency	868 MHz (Europe), 900-928 MHz (America), 2.4 GHz (worldwide)	2.4 and 5 GHz	2.4 GHz
Complexity	Low	High	High
Power Consumption (Battery lifetime)	Very low	High	Medium
Security	128 AES plus application layer	Low	64 and 128 bit encryption
Typical Applications	Industrial control and monitoring, sensor networks, building automation, home control and automation, toys, games	Wireless LAN connectivity, broadband Internet access	Wireless connectivity between devices such as phones, PDA, laptops, headsets

Table 3.2 Suggestions of off-the-shelf wireless evaluation module

Standard	**Sustained Data Rate**	**Network Processor/ Transceiver**	**Protocol Stack**	**Evaluation Module**	**Network Developer**
Texas Instruments					
Bluetooth 2.4 GHz	2.1 Mbps	CC2560	Bluetopia®+LE stack	EZ430-RF256X	Panasonic
Bluetooth 2.4 GHz	1.0 Mbps	CC2540	**Bluetooth® low energy (BLE)**	CC2540DK-MINI, CC2540EM-RD	Amber
Zigbee (2.4GHz)	250 kbps	CC2530 CC2533	Z-Stack TIMAC SimpliciTI	AMB2720, AMBZ420	Amber
Zigbee (2.4GHz)	250 kbps	CC2520 CC2591	Z-Stack TIMAC SimpliciTI	CC2520-CC2591 EMK	-
Bluetooth & WiFi 802.11b/g/n (2.4GHz)	65 Mbps	WL1271	WLAN stack BlueZ *Bluetooth* stack	WL1271-TiWi	LSR
Standard	Sustained Data Rate	Network Processor/ Transceiver	Protocol Stack	Evaluation Module	Network Developer
Microchip					
Bluetooth (2.4GHz)	1.5 Mbps	RN41/2	Onboard embedded Bluetooth stack	RN41/2 – I/RM	Roving Networks
ZigBee 2.4 GHz	250 kbps	MRF24J40 series	ZigBee PRO ZigBee RF4CE SEP suite	MRF24J40MA/ MB/MC PICtail/PICtail Plus	-
WiFi 802.11b	2 Mbps	MRF24WB0 MA/MB	Microchip TCP/IP Stack	Wi-Fi PICtail/PICtail Plus	-
WiFi 802.11b/g	54 Mbps	MRF24WG MA/MB	Microchip TCP/IP Stack	Wi-Fi G PICtail/PICtail Plus	-
WiFi 802.11b/g	1 Mbps	RN131G/C	Microchip TCP/IP Stack	RN-131-PICtail	Roving Networks

Standard	Sustained Data Rate	Network Processor/ Transceiver	Protocol Stack	Evaluation Module	Network Developer
Silicon Labs					
ISM band 2.4 GHz/ Sub-Ghz	1 Mbps	EZRadioPRO subGHz RF transceiver	Snap Network Operating System	Synapse RF Engine Module	Synapse Wireless Inc.
ZigBee 2.4 GHz	250 kbps	EM351/7	EmberZNet PRO ZigBee	EM35X-DEV or EM35X-DEV-IAR	-
Atmel					
ZigBee 2.4 GHz	250 kbps	AT 86RF230	BitCloud - ZigBee PRO	**ATZB-24-A2/B0**	-
EEE 802.11b/g/n	54 Mbps	SPB104	Integrated TCP/IP stack	EVK1100 EVK1101 EVK1104 EVK1105 XMEGA-A1 Xplained SAM3S-EK SAM9M10G45-EK SAMG35-EK SAM9M10-EKES SAM9RL-EK SAM9X25-EK	H&D Wireless
IEEE 802.11b/g/n	30 Mbps	RS9110-N-11-22/02	Integrated TCP/IP stack	XMEGA-A3BU Xplained UC3-L0 Xplained SAM3S-EK SAM9M10G45-EK SAM9G35-EK	Redpine Signals, Inc.
Digi					
ZigBee 2.4 GHz	1 Mbps	XBee ZB	XBee-PRO	XK-Z11-M-W	-
IEEE 802.11b/g/n	65 Mbps	XBee WiFi	API or AT commands to configure WiFi	XK2-WFT-0	-

3.2 Range Study

In this session, we will provide survey about the wireless range transmission. Range is one of the most important parameters of any wireless system; it defines how far a transmitter and receiver can be parted from each other. Data rate, output power, receiver sensitivity, antennas and the intended operation environment influence the practical range of the wireless link [49]. Range is described by Friis equation (Equation 1), which is also often referred to as the link budget. This equation describes the dependency between distance, frequency (wavelength), antenna gain and power. In more down to earth applications, the higher attenuation is expected. Which in means, Ground reduces the effective range in measurement. Based on this equation, in free-space, the path loss is about 80.2 dB over a 100 m distance when operating at 2.445 MHz. We can also notify that half the RF frequency, double the transmission range. The Friss equation requires free space to be valid, and attention to be taken care is, in a typical wireless link transmission waves are reflected and obstructed by all objects at the line of sight by the transmitter antenna. This implies that ground influence has to be considered to do valid range calculations.

$$P_R = P_T\,[G_T\,G_R\,\lambda^2 /((4\pi)^2\,d^2)]] \qquad \text{Equation 1}$$

P_R: Power available from receiving antenna
P_T: Power supplied to the transmitting antenna
G_R: Gain in receiving antenna
G_T: Gain in transmitting antenna
λ: wavelength, where $\lambda = c/f$, c = speed of light, and f = frequency
d: Distance
c: Speed of light in vacuum 299.972458·106 [m/s]

3.2.1 Reliability as Related to Range

From the Friis equation (Equation 1), we can notice that besides RF spectrum usage, embedded wireless systems contain specific characteristics that can help qualify how well they will respond reliably in a wireless system. Link budget is defined as the absolute value of the receive sensitivity plus output power and interference immunity. Therefore, the better the receive sensitivity, the larger the output power and the more interference immunity a solution has, the larger the link budget. The larger the link budget, the less prone the wireless solution will be impacted by RF absorption and interference and thus lead to greater potential for reliability. Reliability is the qualitative sum of link budget plus RF agility with respect to RF spectrum usage; it defines the system's ability to communicate data from point A to point B in a single attempt. The greater the link budget and the greater the RF agility, the more reliable a given wireless solution will be across the same RF spectrum [50].

Reliability is the often overlooked attribute that contribute to the lower power consumption of the overall embedded system. Embedded wireless system that has good reliability shall define the below radio specific characteristics [50]:

- receive sensitivity — how little do the transceivers need to hear in order to make out the communications, measured as a power ratio of decibels referenced to 1mW (dBm);
- output power — how loud can the technology communicate, ultimately talking louder than potential interference, measured in terms of dBm;
- RF agility — the measure of the ability of a technology to move and avoid interference in the RF spectrum, a corollary function of the RF channel size and the number of channels available;
- Interference immunity — a RF technology's ability to communicate in a given channel despite interference as measured by an increase in receive sensitivity, also known as coding gain (dBm). Direct Sequence Spread Spectrum (DSSS) modulation is one of the best technologies in use today that directly improves interference immunity.

Table 3.3 is example of quantitative value noted in datasheet [48] that giving us the picture of the reliability of the embedded wireless system. Proper considerations shall be made towards these RF parameters during the RF transceiver chip selections.

Table 3.3 Sample of wireless characteristics

Parameter	Specification
Frequency	2402 to 2480 MHz
Modulation	802.11b compatibility: DSSS (CCK-11, CCK-5.5, DQPSK-2, DBPSK-1) 802.11g: OFDM (default)
Channels	1-14
Transmission rate (over the air)	1 -11 Mbps for 802.11b/ 6 – 54 Mbps for 802.11g
Receive Sensitivity	-85 dBm typ.
Output level	+ 18 dBm
Maximum RF	+ 10 dBm

3.2.2 Antenna as Related to Range

Antenna design is another key characteristic affecting the communication range. The purpose of an antenna is to provide two way transmissions of data electromagnetically in free space. Antenna in transmit mode transforms electrical signals into RF electromagnetic waves, which propagating into free space; while in receive mode, it transforms RF electromagnetic waves into electrical signals. Thus, the antenna design has to match the impedance of the transmission line feed (typically 50 ohms) and the impedance of free space (377 ohms) [51].

Available antenna types are PCB antennas, whip antennas and chip antennas. Typically, use of PCB antenna requires skilled resources and software due to the antenna is integrated in the product PCB design, it does not involved extra cost, but antenna size impacts at low frequencies; Whip antennas involve higher cost, it is best for matching theoretical range, furthermore the size is not limiting application; While chip antennas have less expensive as compared to whip antennas, but their coverage are in lower range. Antenna design principle is: lower RF frequency, increases the antenna range. In value, it has been commented that reducing the RF frequency by a factor of two doubles the transmission range. However, lower frequency requires a larger antenna. $\lambda/4$ at 2.4 GHz is 3.1 cm.

Antenna selection for wireless application is largely a function of the physical environment [52] in which it will be placed. In order to optimize the RF signal radiated between these two antennas (transmit and receive) requires a clear RF line-of-sight (LOS) path. An RF LOS is called a Fresnel zone, which is a football-shaped tunnel between the two antennas. In practical terms this means that antennas mounted at ground level will have half of the Fresnel zone blocked, which will decrease the communication range. Author in [52] emphasised also the importance of the enclosure of the embedded wireless system. The enclosure is basically the physical environment of the system and the use of metal enclosures is strongly discouraged. With an on-board antenna, the module needs to be out in the open or in some sort of plastic case. A metal case is not recommended, in fact, mounting considerations include the admonition to stay far away from metal objects in general.

3.3 Energy Study

Besides all above mentioned design considerations, equally important in designing any embedded wireless system is characterizing and minimizing the power consumption of the embedded system. Power consumption is a significant and in most cases, the driving requirement of all these wireless data rate applications. The constraint on the wireless design comes from power concerns – especially for portable systems. Low power consumption can be achieved by selecting components with low leakage specifications and by using an ultra-low-power microcontroller (MCU) wireless MCU [53]. The goal of an embedded wireless system is to achieve a perpetually powered system without a necessary maintenance for battery replacement. In achieving this goal, there are more and more emerging researches in energy harvest techniques. Energy harvesting techniques can solve the perpetually powered system problem by supplying and converting energy from the surrounding environment and refilling an energy buffer formed by a battery stack or by super capacitors [54]. A highly efficient solar energy harvester based on Maximum Power Point Tracking (MPPT) for wireless sensor nodes and environmental embedded systems had been proposed, that the designed scavenger can be used with any kind of embedded sensor node, because it is completely independent of the node operation.

In order to maximize battery lifetime, the standby power of the computation and communication circuits in the embedded wireless system must be minimized. The new term to embedded wireless solution is the power efficiency, the measure of a system's passive and active techniques to minimize power consumption. Wireless sensor system should be designed to deal with low duty cycles since the environmental conditions may not change rapidly or the sensors remain in a sleep state until some interesting event happens (detected by some simple front-end electronics [55]. For transmission at GHz carrier a frequency, the power is dominated by the radio electronics (frequency synthesizer, mixers, etc.) besides actual transmits power. Sensors may have very low data rates (<1kbs) and utilize short packet sizes (100's of bits). In order to save power in the wireless module, the designed system must be duty cycled to have ability to turn off during periods of inactivity. The higher the system efficiency the more power is conserved. This form of power-efficient technologies in embedded wireless system, in which it is a solution that continually focuses on minimizing its output power to ensure only the lowest level necessary to communicate, is used. In addition, it is also an embedded wireless solution that can minimize its on-air time.

Another important factor to consider in designing embedded wireless system is the energy source. Thin-film batteries are proper used in embedded systems due to the battery ultra-thin profile and low leakage characteristics [53]. Conventional batteries, such as coin cells, AA lithium batteries and lithium-thionyl-chloride batteries are bulky and non-flexible, and the battery energy to weight ratio factor causes the output energy is quite low. The introduction of thin-film batteries has created a new option for system designers with trade-offs in cost, size and safety. The credit for developing thin film batteries goes to a team of scientists lead by Dr. John Bates. They conducted, since 1997, research at the Oak Ridge National Laboratory for the development of a thin film battery. For over a decade, the size of the thin-film battery has been reduced to the thinnest profile (as small as 0.17mm) of any battery type. The total lifetime capacity of thin film batteries is equivalent to four lithium "AA" batteries. Thin-film batteries are rechargeable, thus batteries only store a portion of total lifetime capacity at any given time. This makes the thin-film battery much safer if it is accidentally shorted or exposed to extreme heat or an open flame.

■4.0 CONCLUSIONS

As utilization increases, and the great progress on development of wireless technologies, wireless industrial flow tomography system will be able to replace conventional wire-based tomography system in many well-testing industrial applications and eliminate the need for costly and space-consuming wired based instalments. Researchers still need to explore quite a few issues during the design of the efficiency embedded wireless tomography system as per the technologies outlined in sections above as far as further development towards more real-time measurements can be designed. An efficient deployment of embedded wireless system in the real world is highly dependent on the ability to have desired data rate, communication latency, reliability, and energy efficiency. Also highlighted here were the typical methods of comparing component datasheets fail to address system-level capabilities such as power-efficiency and reliability. Measuring typical power consumption of the components in use in the system does not tell the complete story of the reliability and efficiency of a particular embedded wireless. The embedded wireless tomography system can be in high efficiency through deep considerations during wireless design phase by looking into wireless characteristics as in terms of RF spectrum usage, Link budget, RF agility, and Antenna and power consumptions. As conclusion, we provide a review on wireless based tomography system and then introduced a set of practical considerations for embedded wireless tomography system design.

Acknowledgement

This study was based on the research supported by the Research Management Centre (RMC) of Universiti Teknologi Malaysia, under the Grant Research University no. Q.J130000.2513.02H67.

References

[1] Phaneeth K. R. Junga, M. Abdelrahman, C. Thurmer, W. A. Deabes. 2008. *Reliable Metal-fill Monitoring System using Wireless Sensor Networks*. In proceedings of the 5th International Conference on Information Technology: New Generations, ITNG. 230–234.

[2] York Trevor A., McCann Hugh, Ozanyan, Krikor, B. 2011. Agile Sensing Systems for Tomography. *IEEE Sensors Journal*. 11(12): 3086 –3105.

[3] Joon-Ha Jin. 2008. *Industrial Process Gamma Tomograpy*. Australia: International Atomic Energy Agency.

[4] Mohamad Elmy Johana, Rahim Ruzairi, Ling Leow Pei, Mohd Hafiz Fazalul, Marwah Omar Mohd. Faizan, Ayob Nor Muzakkir Nor. 2012. Segmented Capacitance Tomography Electrodes: A Design and Experimental Verifications. *IEEE Sensors Journal*. 12: 1589–1598.

[5] Ruzairi Abdul Rahim, Ng Wei Nyap and Mohd. Hafiz Fazalul Rahiman. 2007. Hardware Development of Ultrasonic Tomography for Composition Determination of Water and Oil Flow. *Sensors & Transducers Journal*. 75(1): 904–913.

[6] Hudabiyah Arshad Amari, Ruzairi Abdul Rahim, Mohd. Hafiz Fazalul Rahiman, Jaysuman Pusppanathan. 2011. Front-End Design of an Ultrasonic Tomography Measurement System. *Jurnal Teknologi*. 54 (Sains & Kej.) Keluaran Khas. 289–298.

[7] Mohd Hafiz Fazalul Rahiman, Ruzairi Abdul Rahim, Herlina Abdul Rahim and Nor Muzakkir Nor Ayob. 2012. *Design and Development of Ultrasonic Process Tomography*. InTechOpen book. 11: 211–216.

[8] Mohd Hafiz Fazalul Rahiman, Ruzairi Abdul Rahim, Herlina Abdul Rahim, Nor Muzakkir Nor Ayob. 2012. Novel Adjacent Criterion Method for Improving Ultrasonic Imaging Spatial Resolution. *IEEE Sensors Journal*. 12(6): 1746–1747.

[9] Hoyle B. S. 2005. *Cooperating Sensor Nodes in Spatially Critical Networks for Smart Measurement and Monitoring Systems*. Proc. Smart Object Systems Workshop, UbiComp 2005. Tokyo, Japan. 77–82.

[10] Brian Hoyle. 2010. *Infratography-Wide Area Sensing*. Engineering and Physical Sciences Research Council. 4–5.

[11] York T. A. 2001. Status of Electrical Tomography in Industrial Applications. *Journal of Electronic Imaging*. 10.

[12] York Trevor, A., Stephenson, D. R., Murphy, S., Davidson, John, L., Grieve, Bruce D. 2006. *Ad Hoc Wireless Sensor Tomography*. 493–496

[13] Renee Ka Yin Chin. 2010. *3D Tomographic Imaging Using Ad Hoc And Mobile Sensors*. University of Manchester, PhD Thesis

[14] Mark G. and York Trevor A. 2011. Modified Algorithm for Localisation of Wireless Sensors in Confined Spaces. *IEEE Wireless Sensors and Sensor Networks (WiSNet)*. 29–32.

[15] Tushar Kanti Bera and J. Nagaraju. 2012. Surface Electrode Switching Of A 16-electrode Wireless EIT System Using RF-based Digital Data Transmission Scheme With 8 channel Encoder/decoder Ics. *Measurement*. 45(3): 541–555.

[16] Mathew, B. C., Kiran, K., David, R. A. 2007. *Microwave Tomography Using Dynamic 802.15.4 Wireless Network*. Electro/Information Technology Conference Chicago, II, USA.

[17] Mohammad A. Kanso and Michael G.Rabbat. 2009. *Compressed RF Tomography for Wireless Sensor Networks: Centralized and Decentralized Approaches*. 5th IEEE International Conference on Distributed Computing in Sensor Systems. 173–186.

[18] R. C. Qiu, M. C. Wicks, L. Li, Z. Hu, S. J. Hou, P. Chew, and J. P. Browning. 2010. *Wireless Tomography, Part I: A Novel Approach to Remote Sensing*. 5th International Waveform Diversity & Design Conference. 000244–000256.

[19] R. C. Qiu, Z. Hu, M. C. Wicks, S. J. Hou, L. Li, and J. L. Garry. 2010. *Wireless Tomography Part II: A System Engineering Approach*. 5th

International Waveform Diversity & Design Conference, 2010. 277–282.

[20] Peng Zhang and Robert, C. Qiu. 2010. *Wireless Tomography, Part III: Compressed Sensing for Ultra-wideband Signals*. 5th International Waveform Diversity & Design Conference. 35–39.

[21] Hu, Z., Hou, S., Wicks, M. C., Qiu, R. C. 2013. *Wireless Tomography in Noisy Environments Using Machine Learning*. IEEE Geoscience and Remote Sensing.

[22] J. Bonior, Z. Hu, S. Hou, S. Corum, B. McNew, N. Guo, R. C. Qiu, and M. C. Wicks. 2012. Prototyping of a Wireless Tomography System Using Software-defined Radio. In *Proc. IEEE Waveform Divers. Design Conf.* Jan. 2012. 293–297.

[23] Deabes, W. A., Abdallah Mohammed A., Elkeelany Omar, Abdelrahman, M. A. 2009. Reconfigurable wireless stand-alone platform for Electrical Capacitance Tomography. *Computational Intelligence in Control and Automation*. 112–116.

[24] Justin Helmig. 2002. *Programming Considerations for Developing Next-Generation Wireless Embedded Applications*. Texas Instrument White Paper.

[25] Bernhard Andretzky. 2005. *FPGAs Build Bridges To Wireless Connectivity*. Penton Media, Inc. White Paper.

[26] Cypress. 2011. WirelessUSB™ Dual Antenna Design Layout Guidelines, Application note.

[27] Esteban Egea-Lopez, Alejandro Martinez-Sala, Javier Vales-Alonso, Joan Garcia-Haro, and Josemaria Malgosa-Sanahuja. 2005. Wireless Communications Deployment in Industry: A Review of Issues, Options and Technologies. *Computers in Industry*. 29–53.

[28] M. Park, C. Cordeiro, E. Perahia, and L. Yang. 2008. *Millimeter-wave multigigabit WLAN: Challenges and feasibility*. IEEE Int. Symp. Pers. Indoor Mobile Radio Communication.

[29] C. Park and T. S. Rappaport. 2007. Short-range wireless communications for next-generation networks: UWB, 60 GHz millimeter-wave WPAN, and ZigBee. *IEEE Wireless Commun*. 14(4): 70–78.

[30] LS Research, LLC. 2012. *Integrated Transceiver Modules for WLAN 802.11 a/b/g/n,Bluetooth, Bluetooth Low Energy (BLE), and ANT*. Technical Datasheet.

[31] Sinem Coleri Ergen. 2004. *ZigBee/IEEE 802.15.4 Summary*. Laboratoire PRiSM.

[32] Andreas Willig. 2008. Recent and Emerging Topics in Wireless Industrial Communications: A Selection. *IEEE Transactions on Industrial Informatics*. 4(2): 102–124.

[33] Atmel. 2009. *Low Power 2.4 GHz Transceiver for ZigBee, IEEE 802.15.4, 6LoWPAN, RF4CE and ISM Applications AT86RF230*, Technical Datasheet.

[34] Charlotte Seem and Espen Slette. 2010. *Using CC2591 Front End with CC2520*, TI Application Note AN065.

[35] Digi International Inc. 2011. *XBee® Wi-Fi Embedded Wi-Fi Module for OEMs*, Technical Datasheet.

[36] Digi International Inc. 2008. *XBee® & XBee-PRO® ZB-ZigBee® Embedded RF Module Family for OEMs*, Technical Datasheet.

[37] H&D Wireless AB. 2011. *SPB104-WiFi 802.11b+g SDIO Evaluation Kit*. Technical Datasheet.

[38] Microchip. 2008. *MRF24J40MA Data Sheet 2.4 GHz IEEE Std. 802.15.4™ RF Transceiver Module*. Technical Datasheet.

[39] Microchip. 2010. *MRF24J40 Data Sheet IEEE 802.15.4™ 2.4 GHz RF Transceiver*. Technical Datasheet.

[40] Microchip. 2012. *MRF24WG0MA PICtail™/PICtail Plus Daughter Board Information Sheet*. Technical Datasheet.

[41] Niclas Lindblom. 2011. *Small, Smaller, Smallest - RF Communication Protocols for Low-Power Wireless Systems*. IAR Systems White Paper.

[42] Redpine Signals, Inc. 2011. *RS9110-N-11-02 802.11bgn WLAN Module*. Technical Datasheet.

[43] RovingNetworks. 2012. *RN-42/RN-42-N Class 2 Bluetooth*. Technical Datasheet.

[44] Synapse Wireless, Inc. 2010. *SYNAPSE RF Engine IEEE 802.15.4 RF Modules*. Technical Datasheet.

[45] Silicon Laboratories. 2012. *EM35x IEEE 802.15.4 and ZigBee Compliant SoC Family*. Technical Datasheet.

[46] TI. 2011. *Bluetooth® v2.1 + Enhanced Data Rate (EDR) Module*. Technical Datasheet.

[47] TI. 2011. *True System-on-Chip Solution for 2.4-GHz IEEE 802.15.4 and ZigBee Applications*. Technical Datasheet.

[48] RovingNetworks. 2012. *RN-131G & RN-131C 802.11 b/g Wireless LAN Module*. Technical Datasheet.

[49] Tor-Inge Kvaksrud. 2008. *Range Measurements in an Open Field Environment*. Application Note.

[50] Jim Davis. 2009. *Reliability vs. Power in Embedded Wireless Applications–What Datasheets Don't Say*. Mobile Handset Design Guideline.

[51] Mahesh Kiwalkar. 2011. *Design and Layout Guidelines for Matching Network and Antenna for WirelessUSB™ LP Family*. Cypress application note.

[52] Rabbit Semoconductor. 2010. *Designing with Wireless Rabbits*. Rabbit Semoconductor Technical Note.

[53] Silicon Laboratories Inc. 2012. *Implementing Energy Harvesting in Embedded System Designs*. Technical White Paper.

[54] Davide Brunelli, Luca Benini, Clemens Moser and Lothar ThieleDesign. 2008. *An Efficient Solar Energy Harvester for Wireless Sensor Nodes*. Automation and Test in Europe. 104–109.

[55] Anantha Chandrakasan, Rajeevan Amirtharajah, SeongHwan Cho, James Goodman, Gangadhar Konduri, Joanna Kulik, Wendi Rabiner, and Alice Wang. 1999. *Design Considerations for Distributed Microsensor Systems*. Proceedings of the IEEE 1999. 279–286.

[56] R. Abdul Rahim. S.Z Mohd. Muji. January 2013. Optical Tomography : Image Improvement using Mix Projection of Parallel and Fan Beam Mode. *Measurement Journal (ISSN: 0263-2241) Elsevier Science*. 46: 1970–1978.