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Industrial Wireless Sensor Networks (IWSN): Design And Challenges

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Abstract: *The objective of this research paper is to design and implement wireless sensor networks (WSN) for various monitoring & control applications in industry. In today's competitive market the industries are facing growing demands to improve process efficiencies to comply with environmental regulations and meet corporate financial objectives. Therefore, the Wireless Sensor Network (WSN) for industrial automation and process control are becoming more prevalent. Mature industries such as oil and gas refineries, waste water treatment and delivery, electricity generation, natural gas distribution have migrated from wired to wireless control networks over the past decades. There are number of challenges in migrating from a wired to a wireless control network. The main aim of this paper is to discuss the challenges in implementing WSN. The purpose is also to show how to evaluate some specific parameters of a WSN employed for industrial application to obtain useful information for its setup optimization in the presence of interference.*
***Keywords**: Industrial wireless sensor network (IWSN), Ultra Wideband (UWB), Wireless mart, Zigbee, Design challenges.*

I. Introduction

In the industrial application systems, wireless tiny sensor nodes are installed on industrial equipment and monitor the parameter critical to each equipment's efficiencies based on a combination of measurements such as vibration, temperature, pressure and power quality. These data then wirelessly transmitted to a sink node that analyzes the data from each sensor. A typical industrial wireless sensor Network (IWSN) scenario is shown in fig.1. Here, a control person controls the Tank level, ON-OFF switch, Pressure, Temperature and Humidity of an industrial Plant. Due to unique characteristics and technical challenges, develop a WSN for industrial applications require a combination of expertise from several different disciplines. First of all, industrial expertise and knowledge are required for application domain-specific knowledge. Second, sensor technology expertise is essential to fully understand issues associated with sensor calibration, transducer and Clock drift.

Fig.1 Industrial Wireless Sensor Networks (IWSN)

Third, RF design and propagation environment expertise is necessary to address communication challenges and RF interference problems in industrial environments [2]. Finally, networking expertise is needed for understanding the hierarchical network architectures and integrating different networks, which are required for industrial WSNs (IWSNs) to provide flexible and scalable architectures for heterogeneous applications. A sensor network is composed of a large number of sensor nodes that are deployed in a wide area with very low powered sensor nodes. The wireless sensor networks can be utilized in a various information and telecommunications applications. The sensor nodes are very small devices with wireless communication capability, which can collect information about sound, light, motion, temperature etc and processed different sensed information and transfers it to the other nodes. The below figure illustrates the WSN scenario.

Basic Characteristics of WSNs

Wireless Sensor Networks are:

- Self-configuration, Self-healing, Self-optimization, and Self-protection capabilities
- Short-range broadcast communication and multi-hop routing
- Dense deployment and cooperative effort of sensor nodes
- Frequently changing topology due to fading and node failures
- Severe limitations in energy capacity, computing power, memory, and transmit power.

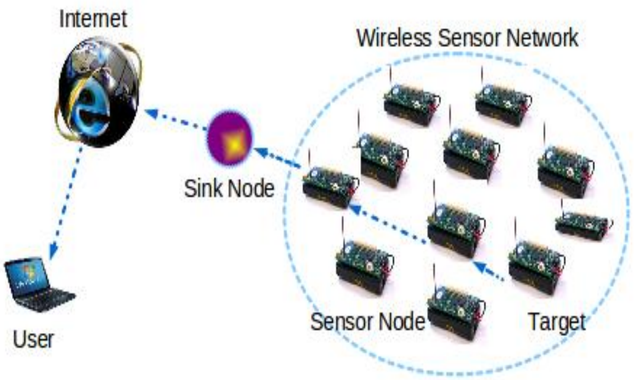

Fig 2: Illustrations of Wireless sensor network

Some key drawbacks also exist which are actually delaying a wide deployment of these systems for industrial applications. One critical issue is the poor reliability of WSNs when some types of in-channel radio interference occur. This situation is typical for WSNs that transmit on radio channels shared with other communication systems and, hence, are plagued by radio disturbance, for instance, the 2.4-GHz industrial, scientific, and medical (ISM) band (2.4–2.4835 GHz). In this band, several sources of interference can be encountered, including, for example, IEEE 802.11b/g wireless local area networks (WLANs)[3], IEEE 802.15.4 [4], and IEEE 802.15.1 (Bluetooth) enabled devices, microwave ovens, cordless phones, etc. Moreover, severe timing constraints may often be required, which means some key drawbacks are actually delaying a wide deployment of these systems for industrial applications, due to some technical problems still far from being completely solved.

The most typical effect of interference is signal degradation, which occurs at the WSN receivers when the incoming useful signal is affected by interference. To reduce this effect, some communication standards employ sensing mechanism such as the carrier-sense multiple access with collision avoidance (CSMA/CA) protocol. This mechanism enables multiple users to show the same physical medium, avoiding collisions and consequently, signal degradation [13].

A CSMA/CA compliant network node typically senses the in channel power before transmitting. If the measured power is below a given threshold, which means that the medium is actually not busy, then the transmission may begin otherwise after a random back off period, another attempt is performed. If the interference at the WSN receiver is higher than a prefixed threshold then the channel is assumed to be busy and any node wishing to transmit is forced to wait and delay the delivery of data packets. A specific high layer protocol is used that is capable of both cyclic polling and acyclic alarm management. The purpose is to show how to measure some specific parameters of an industrial WSN to obtain valuable information for its setup optimization in the presence of interference [4].

Unlike the office network, the industrial environment for wireless sensor networks is harsher due to the unpredictable variations in temperature, pressure, humidity, present of heavy equipments etc. so before moving to the real implementation, it is necessary to test some of the communication pattern in simulation environment [6]. The wireless sensor networks can be deployed for online monitoring of voltage, humidity, temperature, pressure, light and acceleration inside a building [7].

Mostly, the classification of WSN is based on their application objectives, traffic characteristics and data delivery requirements.WSN have different characteristics in terms of their applications and requirements. There are certain design problems that are common to most of the sensor networks when communicating information over the wireless channel, the design consideration in view of WSNs in industries, the problem like interference and other issues that could be encountered in WSN are discussed. Some challenges are discussed based on the result from the simulator Castalia based on OMNET++.

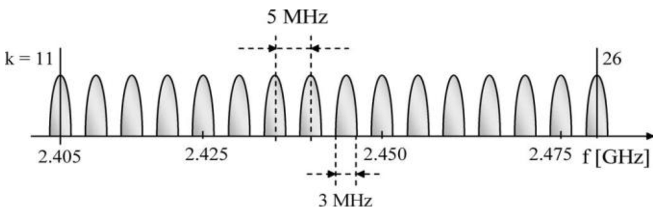

Fig 3: Frequency channels of IEEE 802.15.4 inside the ISM band.

This figure include 16 channels each 3MHz bandwidth. In the field practitioners wishing to optimize the setup of an industrial IEEE 802.15.4 WSN in the presence of interference [5].

An ultra-secure and ultra-reliable wireless network infrastructure supports all types of plant safety, reliability and efficiency requirements. These include:

- Equipment health monitoring – preventing premature failure of rotating equipment by monitoring vibration
- Alerting – indication when a safety shower is used or when employees enter unsafe environments
- Inventory management – monitoring valve position, tank level and other measurements during product movement
- Closed-loop measurement – with wireless communications occurring in one second or less , non-critical measurement and control can occur
- Wireless SCADA – improve the speed of communication of remote field measurements and span transmission distances of several miles to supervisory control systems
- Mobile operator – allowing process control to take place in the field with portable, wireless tablet computers, real-time field observations can be acted upon
- Security monitoring – easily improve security with wireless monitoring of gates, motion detection and video surveillance
- Environmental compliance – remotely monitor air and water discharge points to prevent excursions and ensure regulatory compliance
- Video surveillance – establish perimeter security with remote video cameras
- Enterprise asset management

II. Challenges, Design And Goals Of Industrial Wsn

The industrial applications of wireless sensor network have some challenges for realization of IWSN that can be:

- **Challenge: Resource constraints**

Constraints:

a. -Battery energy
b. -Limited memory
c. -Limited Processing Capabilities
d. -Bandwidth constraint

- **Design Goal: Resource-efficient design**

1) Energy saving with energy-efficient protocols
A Energy-aware routing on network layer
B -Energy-saving mode on MAC layer
For certain FEC (forward error correction) codes, hop-length extension decreases energy consumption
-Hardware optimizations.
-**Sleeping schedules** to keep electronics inactive most of the time, dynamic optimization of voltage, and clock rate.
-System-on-chip (SOC) technology for low power consumption by integrating a complete system on a single chip (ZigBee SOC, CC2430, EM250).
2) Local Data Processing
3) Energy Recovery/Acquisition: Energy harvesting technique extracts energy from environment

- **Some approaches:**

-Photovoltaic cell with rechargeable battery.
-Background radio signal: small energy vibrations, thermoelectric conversion.
-RF signal transmission: safety issue employing piezoelectric materials.

- **Challenge: Data redundancy**

High Density in network topology cause redundant data in both spatial and temporal domain
Spatial correlation: redundant data possibly from nearby sensors
Temporal correlation: redundant data from consecutive observation

- **Design Goals: Data fusion and localized processing**

Data aggregation and fusion
- Locally filter the sensed data and transmit only the processed one.
- Only necessary information is transported to the end-user.

Intermediate node checks the contents of incoming data and then combines them by eliminating redundant information under some accuracy constraints

- **Challenge: Packet errors and variable-link capacity**

Attainable capacity and delay at each link depends on
- Location
-Interference level perceived at the receiver varying characteristics of the link over space and time due to obstructions and noisy environment.

- **Design Goals: Fault tolerance and reliability**

-Sensed data should be reliably transferred to the sink node (especially mission-critical information)
-Programming/command and queries should be reliably delivered to the target sensor node to assure the proper functioning.
-To combat the unreliability, verification and correction on each communication layer are required automatic repeat request (ARQ): not suitable for real time system
-forward error correction (FEC)
-Improve the error resiliency more than ARQ
-Radio-modulation techniques to reduce interferences and improve reliability
-Direct sequence spread spectrum
-Frequency hopping spread spectrum
Benefits of SSM:
-Multiple access
-Anti-multipath fading
-Anti-jamming

- **Challenge: Security**

Security for external attacks and intrusion
Passive attacks: eavesdropping on transmissions, traffic analysis, and disclosure of message contents. **Active attacks:** modification, fabrication, and interruption (in case of IWSN, node capturing, routing attacks, or flooding)
External denial-of-service

- **Design Goal: Secure design**

Low level and high level security should be addressed
-key establishment and trust control, secrecy and authentication, privacy, robustness to communication DoS, secure routing, resilience to node capture.
-secure group management, intrusion detection, secure data aggregation, Security overhead should be balanced against QoS.

- **Challenge: Dynamic topologies and harsh environmental conditions**

In harsh industrial environments, the topology and connectivity of the network may vary due to -link and sensor-node failures
-a portion of sensor nodes to malfunction

- **Design Goal: Adaptive network operation**

Adaptability enables to cope with dynamic wireless-channel conditions and new connectivity requirements for new industrial processes Adaptive signal-processing algorithms and communication protocols are required to balance the trade-offs among
-Resources
-Accuracy
-Latency
-Time synchronization requirements

- **Challenge: Quality-of-service requirements**

-Accuracy between the data reported and what is actually occurring in the industrial environment -Time sensitive data should be reached in a timely manner Different IWSNs have different QoS requirements and specifications

- **Design Goal: Application-specific design and Time synchronization**

-Designs and techniques should be based on the application-specific QoS requirements.
-Existing time synchronization strategies designed for other traditional wired and wireless networks may not be appropriate for IWSNs due to:

- Resource and size limitations
-lack of a fixed infrastructure
-dynamic topologies
-Adaptive and scalable time-synchronization protocols are required for IWSNs.

- **Challenge: Large-scale deployment and ad hoc architecture**

-Large number of sensor nodes randomly spread over the deployment field.
-Need for autonomous establishment of connections and maintenance of network connectivity.

- **Design Goal: Low-cost and small sensor nodes and Self-configuration and self-organization**

-To accomplish large scale deployments feasible hardware cost should be minimized
-Commercial release:
-Smart Dust motes
-uAMPS
-CC2430 and EM250
-ZigBee SOC
self-organizing architectures and protocols are required for supporting the dynamic topologies caused by node failure/mobility/temporary power-down/addition of new nodes
-large-scale node deployments

- **Challenge: Integration with Internet and other networks**

-IWSN needs to provide service for querying the network to retrieve useful information from anywhere and anytime.
-Should be remotely accessible from the Internet
-Need to be integrated with the Internet Protocol (IP) architecture

- **Design Goal: Scalable architectures and efficient protocol**

Needs to support heterogeneous industrial applications necessary to develop flexible and scalable architectures to accommodate the requirements of various applications in the same infrastructure. Modular and hierarchical systems interoperability with existing legacy solutions such as field bus and Ethernet-based systems

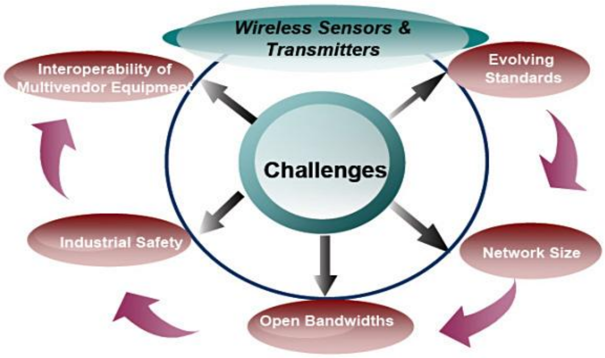

Fig.4: Challenges in Industrial Wireless Sensor Networks (IWSN)

III. Design Principles And Technical Approaches

Industrial wireless sensor network (WSN) is broadly classified into three categories:

1. Hardware Development.
2. Software Development.
3. System Architecture and Protocol Design.

A. Hardware development:

1. **Low power and low cost sensor node development**: the hardware architecture of a typical industrial sensor node is composed of four basic components

- Sensor
- Processor
- Transceiver
- Power source

Generally the life time of IWSN shows a strong dependence on battery capacity, in a multihop IWSN, each node plays the dual role of data originator and data router.

2. **Radio technologies:** The reliability of the data may suffer from noise, co channel interference, multipath propagation and other interference signals can be classified in two different categories: Broadband and Narrowband.

In an industrial environment broadband interference can be caused by motors, inverter, computers, electric switch contact, voltage regulator, pulse generators, thermostats and welding equipments. On the other hand narrow band interference can be caused by UPS system, electronic ballasts, test equipment, cellular network, radio transmitter, signal generator and microwave equipment [1].

B. Software development:

1. **API**: In IWSN, the application software should be accessible through a simple application programming interface.
2. **System Installation and Commissioning**: During installation of IWSN, the system owner must be able to indicate to the system what a sensor is monitoring and where it is.

IV. IEEE 802.15.4 Standard And High Layer Monitoring Protocol

IEEE 802.15.4 technology enables many applications of WSN. The key features of 802.15.4 wireless technology are low complexity, low cost, low power consumption, low data rate transmission to be supported by cheap either fixed or moving devices. The main field of applications of this technology is implementation of WSN. The implementation of WSN is possible when decreasing the interference. For this, a high layer protocol has been designed and implemented on a WSN for industrial monitoring. A high layer protocol, which is based on a master slave relationship, has been designed and implemented on a WSN for industrial monitoring. The protocol performs two classic tasks:

1. Periodical polling of each slave for receiving data from monitoring sensors (cyclic task).
2. Asynchronous alarm transmission, which is able to handle critical events from peripheral sensors (acyclic task).

A. Cyclic Task:

The cyclic task is performed according to a round robin fashion.

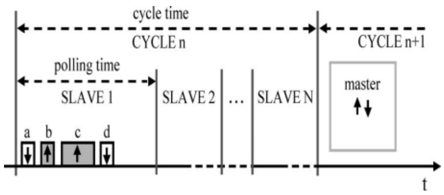

Fig 6: Packet exchange between the master and the slave within a polling time.

At time instant S_n the Master transmits a request, which is received after a time interval τ_{MS} , which is given by

$$T_{MS} = t_{BM}+t_{TXM} \quad ....(1)$$

Where t_{BM} is the initial back off period needed to access the channel by the master and t_{TXM} is the time actually necessary from the master to the slave.

Then, after the time necessary to send the acknowledgement from the slave to the master, the queried slave replies with a response received by the master after a time interval τ_{SM} , which is given by:

$$\tau_{SM} = t_{ACK} + t_{BS} + t_{TXs} \quad ......(2)$$

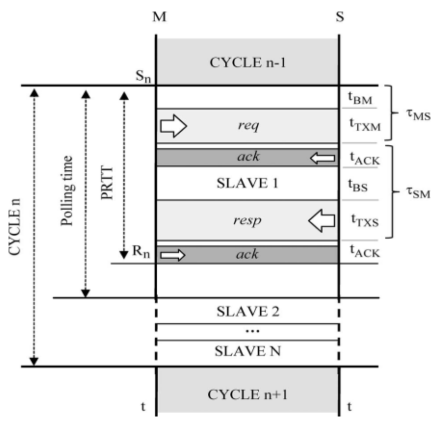

Fig 5: Time diagram of the master and slave communication.

where t_{BS} is the initial back off period needed to access the channel by the slave and t_{TXNs} is the time actually necessary to transmit the frame from the slave to the master.

Finally, the master sends an acknowledgement frame to the slave and the polling ends at the instant R_n.

The difference between R_n and S_n is the polling round trip time (PRTT), which represents the time employed by the master to execute the complete query of a slave. It may vary from cycle to cycle.

$$PRTT= R_n-S_n =t_{BM} + t_{TXm} + t_{BS} + t_{TXs} + 2t_{ACK} \quad …….(3)$$

PRTT is a measurable parameter from which interesting information about both the presence and the effect of interference source influencing the wireless channel can be deduced. If interference is not present, only one channel access attempt is performed by both the master and slave and consequently, τ_{MS} and τ_{SM} are uniformly distributed independent random variable.

A second parameter useful in the analysis of interference effects is the Experimental Cycle Time(ECT), which is defined as the difference between two consecutive arrival times $R^i_n - R^i_{n-1}$ from the i[th] slave i.e.,

$$\underbrace{ECT^i}_{\text{Deterministic}} = R^i_n - \underbrace{R^i_{n-1} = S_n - S_{n-1}}_{\text{Rando}} + (PRTT^i_n - PRTT^i_{n-1}) \quad …...(4)$$

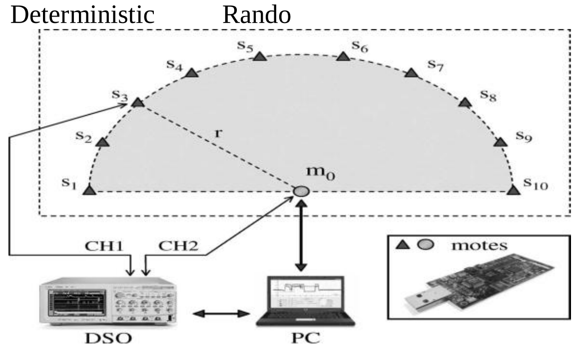

Fig 7: Test bed architecture in the case of ten slaves (N=10)

A. **Without Interference**- A first set of tests has been carried out with a reduced number of slaves (three) namely S_1, S_5 and S_{10} in the absence of interference signals. The outcome of such a test allowed us to determine the value of the polling time considered suitable for a stable operation of a WSN.
B. **With interference-** Further test have been carried out at the same conditions of the aforementioned experimental case but in the presence of adhoc generated interference. In particular, we have experimented with the following two types of disturbance:
1. Additive white Gaussian noise (AWGN) interference of 5 MHz bandwidth and centered at the same frequencies of the WSN exploited channel.
2. Impulsive interference, which is obtained by modulating the amplitude of the aforementioned.

AWGN interference with a periodical sequence of bursts with variable duty cycle λ_B and burst period T_B of either 100 or 300ms.To carry out such test, a suitable signal generator Agilent Technologies E4433B(250 KHz- 4GHz) and a log periodic antenna EMCO 3146 have been used, which are oriented towards the test bed at a distance of 1 meter from it.

- **Selecting a Wireless Design Partner for an Industry**

The decision to implement wireless technology at a terminal or tank farm is a strategic choice, enabling an overall asset monitoring and control strategy that will provide significant performance and economic benefits beyond avoiding wiring costs. The right decision will help improve safety, optimize the facility and ensure compliance. Most industrial sites implementing wireless are very satisfied with their first applications and adding more wireless applications throughout the operation. Ensuring performance, security and reliability for many wireless applications can be complex, however.

Without expertise and a common and scalable wireless management infrastructure, end users will find it difficult to deploy, manage and maintain their wireless applications. Your supplier should have:

- Experience implementing wireless systems in industrial environments.
- An integrated solution, including field devices, wireless network and integration with client system
- Desired performance such as communication speed, device battery life, security and reliability.

Among major control system and instrumentation suppliers, Honeywell has taken a leading role in supporting the advancement of industrial wireless. Honeywell is a charter member of the ISA SP100 committee, WINA and ZigBee. It was also the first distributed control system (DCS) supplier to provide a wireless solution to its customers, installing over 35 million wireless devices worldwide. These wireless installations have logged more than 500,000,000 operating hours.

V. Conclusion

The IWSN have the potential to improve productivity of industrial systems by providing greater awareness, control and integration of business process. Other open issues include optimal sensor node deployment, localization, security and interoperability between different IWSN manufacturers. In this paper, a general and meaningful experiment case study has been presented, involving a real life IEEE 802.15.4 WSN using CSMA/CA employed for industrial applications, under the presence of interference. The analysis has been performed with the network operating according to both cyclic and acyclic tasks. The other work is to detect the occurrence of possible interference effects and understand how to optimize the network setup. All the presented measurement activities can also be applied to WSNs already installed and operating in a real industrial environment.The Table1 shows various performance parameters of major companies providing IWSN solutions to the industry. For example, Type of Application, Communication technology, Transmission Technology, Maximum Transmit/Receive Range, Fastest updates time, Number of Field Units per Network, Gateway Interface, and Wireless Standard etc. The task of an IWSN design engineer is to choose the optimum combination of different design parameters for a typical IWSN application scenario as give in table1.

Table1: Comparison of IWSN performance parameters:

COMPANY	**Accutech**	**Honeywell**	**Emerson**
Example Application	Pressure, temperature, level measurement, discrete input	Pressure, temperature, level, position measurement, discrete input/output	Pressure, temperature, level, position, vibration measurement, discrete input
Communication technology	Star Point to Point Communication - Base station that transmits and receives data from multiple field units	Star Mesh Network - The Honeywell One Wireless network is formed with mutli-protocol communication nodes, called multinodes, which support both 802.11 and field sensor-based transmissions.	Mesh Network - The Dust Mesh network with self healing and self organization features
Transmission Technology	900MHz Frequency Hopping Spread Spectrum (FHSS)	2.4 GHz Frequency Hopping Spread Spectrum (FHSS)	2.4 GHz Direct sequence spread spectrum (DSSS)
Maximum Transmit/Receive Range	Up to 5000ft (~1500m)	Up to 6 miles (10 km) multinode to multimode communication; sensor to multinode designed for over 2,000 ft (600m)	200 met
Fastest update time	1 sec	1 sec	4 sec
Number of Field Units per Network	Up to 100 wireless field units per base radio	Each multinode accepts signals from up to 20 wireless transmitters reporting at 1 second, and up to 400 transmitters reporting at slower rates.	Up to 100 devices for a single wireless gateway
Gateway Interface	Modbus	802.11 Wi-Fi	Ethernet, Modbus
Wireless Standard	Uses proprietary protocol	ISA100.11a	Wireless Hart

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