Industrial Wireless Networking With Resource Constraint Devices

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INDUSTRIAL WIRELESS NETWORKING WITH RESOURCE CONSTRAINT DEVICES

DISSERTATION

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on account of the decision of the graduation committee,
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by

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born on May 28, 1985
in Chittagong, Bangladesh
This dissertation is approved by:
Prof. dr. ing. P.J.M. Havinga (supervisor)
Dedicated to my son, Kushal

who has grown into a wonderful two-and-half year old in spite of his father spending so much time away from him working on this dissertation
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work and life issues. Many thanks Viet Duc for the very warm friendship and for accepting to be my paranymph during my defense.

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Kallol Das

Enschede, October 2015
Abstract

During the last decade, wireless technologies have revolutionized the industrial automation sector by enabling wireless sensing and actuation for industrial applications. Most of these recently developed industrial standards are built on top of IEEE802.15.4 interface, which uses 2.4GHz frequency band for communication. Because of the wide use, reliable communication with low latency cannot always be guaranteed on this frequency band. While satisfying the requirements of monitoring applications quite well, current industrial standards have several limitations to address the requirements of time-critical control applications. For instance, owing to the use of a centralized network management scheme, widely used industrial standards such as WirelessHART and ISA100.11a cannot handle network disturbances in a real-time manner. Moreover, the I/O devices (sensors and actuators) in these systems have to go through a complex network joining process, which takes a lot of time and energy.

The network devices in industrial applications are typically expected to run for a long time without maintenance. Replacing batteries and main powering of these nodes are often not practical in industrial environments. To address this issue, energy harvesting technologies are becoming popular as an alternative power source for the industrial I/O devices. However, present energy harvesters can only produce a little amount of energy that forces the harvester powered I/O devices to shut down frequently. Consequently, these I/O devices need to re-join the network to resume their task, which consumes additional energy. Clearly, this is a huge overhead for resource constraint I/O devices.

To deal with the above mentioned limitations of existing industrial systems, we propose two hierarchical network management schemes where blocks of communication resources are delegated to the routers to locally manage the I/O devices. The proposed schemes are able to cope with the network disturbances quickly with low overhead. Next, we propose a fast network joining scheme for I/O devices that is
able to reduce the network joining overhead and make the network more suitable for harvester powered I/O devices. In addition, we propose a data publication scheme for the harvester powered I/O devices by utilizing spatial diversity that can improve the communication reliability. Last but not least, with the advances in energy harvesting technologies, a new industrial application class called *fit-and-forget system*, in which I/O devices are only powered by energy harvesters, is attracting much attention. To address the requirements of such I/O devices with strict energy budget, we propose an asynchronous communication scheme that allows harvester powered I/O devices to transmit their data whenever they harvest enough energy.
Gedurende het laatste decennium hebben draadloze technologieën voor een revolutie gezorgd binnen de industriële automatiseringssector, door het mogelijk maken van draadloos meten en bedienen in industriële toepassingen. De meeste van deze recentelijk ontwikkelde industriële standaarden zijn gebouwd op een IEEE802.15.4 interface, welke de 2.4GHz frequentieband gebruikt voor communicatie. Vanwege het wijdverspreide gebruik kan betrouwbare communicatie met lage latentie niet altijd gegarandeerd worden op deze frequentieband. Huidige industriële standaarden hebben, ondanks dat zij aardig voldoen aan de eisen van monitorende applicaties, verschillende beperkingen om aan de eisen van tijd-kritische controle applicaties te voldoen. Bijvoorbeeld vanwege het gebruik van een gecentraliseerd netwerkbeheer, kunnen veelgebruikte industriële standaarden als WirelessHART en ISA100.11s niet op een real-time manier met netwerkverstoringen omgaan. Bovendien zullen de I/O devices (sensoren en actuatoren) door een complex netwerk toetredingsproces moeten gaan, wat veel tijd en energie kost.

Van netwerk apparaten in industriële applicaties wordt verwacht dat zij lang mee gaan zonder onderhoud. Het vervangen van batterijen of bedraad voeden van deze nodes is vaak niet praktisch in industriële omgevingen. Om dit probleem aan te pakken, worden energy-harvesting technologieën steeds populairder als een alternatieve energiebron voor industriële I/O devices. De huidige energy-harvesters echter, kunnen maar een kleine hoeveelheid energie produceren, wat harvester angedreven I/O devices dwingt om regelmatig uit te schakelen. Hierdoor moeten I/O devices zich opnieuw bij het netwerk aanmelden om hun taak te hervatten en dit kost additionele energie. Dit is duidelijk een grote overhead voor resource beperkte I/O devices.

Om bovenstaande beperkingen van bestaande industriële systemen aan te pakken, stellen wij twee hiërarchische netwerk management systemen voor, waarbij blokken van communicatie resources gedelegeerd worden aan de routers, om zo-
doende lokaal de I/O devices te beheren. De voorgestelde systemen kunnen snel en met een lage overhead omgaan met netwerkstoringen. Tevens stellen wij een snel netwerk aanmeldschema voor I/O devices voor, dat de toetredings overhead kan verminderen en dat het netwerk geschikter kan maken voor harvester aangedreven I/O devices. Bovendien stellen wij een data publicatie schema voor harvester aangedreven I/O devices voor, waarbij gebruik gemaakt wordt van spatiële diversiteit om zo de communicatie betrouwbaarheid te verbeteren. Last but not least, krijgt dankzij de vooruitgang in energy-harvesting technologieën, een nieuwe industriële applicatie klasse genaamd fit-and-forget systeem, waarbij I/O devices alleen aangedreven worden door energy harvesters, veel aandacht. Om te voldoen aan de eisen van dergelijke I/O devices met een strikt energie budget, stellen wij een asynchroon communicatie systeem voor, dat harvester aangedreven I/O devices de mogelijkheid geeft om hun data te verzenden wanneer zij genoeg energie hebben vergaard.
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Real-time monitoring and precise control of the machinery are essential to maintain the quality of the product in a factory and keep facilities secure. Traditionally, industrial monitoring and control applications rely on wired communication networks such as Fieldbus H1 [1], Profibus [2] and CAN [3], in which hundreds of sensors and actuators are mounted on different machine parts to monitor their physical conditions and control them whenever necessary. While such technologies have supported most of the industrial applications over the past few decades, they are increasingly proving to be inadequate to meet the requirements of the modern industrial applications. The primary reason of this is the very rigid nature of wired infrastructures. For instance, existing technologies are unable to monitor difficult to reach areas in the factory (e.g., moving machine parts) as it is not always feasible to put wires in those areas [4].

Meanwhile, wireless technologies have the potential to revolutionize the industrial automation sector as they possess several significant advantages over the conventional wired counterparts such as reduced installation cost and time, improved flexibility during plant extension, lowered maintenance cost, and increased scalability and robustness. Additionally, wireless technologies can procreate new classes of industrial application (e.g., fit and forget system, distributed sensing and control, embedded automation, etc.), which were not envisioned during the era of wired industrial networks. In spite of having the above mentioned benefits, industrial wireless sensor networks face a number of challenges such as interference from other radio communication systems operating on the same/adjacent frequency band(s), lack of long lasted power supply, limited throughput, lack of reliability due to harsh radio propagation environment, high communication latency, limited range and scalability, etc.

The main aim of this thesis is to design reliable and energy efficient wireless com-
munication schemes that will be able to fulfill the requirements of the modern indus-
trial monitoring and control applications. The rest of this chapter is organized as
follows. Firstly, we give a comparative overview between traditional wireless sen-
sor networks (WSNs) and industrial wireless sensor networks (IWSNs) in Section
1.1. Section 1.2 and 1.3 then elaborate on the characteristics and application require-
ments of IWSNs, respectively. Section 1.4 describes the limitations of the current
wireless technologies to address the requirements of modern industrial automation.
In Section 1.5, we discuss the research objectives of this thesis and, linked to this,
how our research question will be addressed. Next, the main contributions of this
thesis are summarized in Section 1.6. Finally, we present the outline of this thesis in
Section 1.7.

1.1 Traditional WSNs versus IWSNs

WSNs typically consist of low powered computing devices that are capable of trans-
ferring small data packets. During the last few decades, WSNs have been widely
implemented in a lot of applications such as home automation [5], wild-life mon-
itoring [6], health-care [7], under-water research [8], etc. Despite having different
objectives, successful data dissemination is the most important goal in all of these
cases. A typical wireless sensor node has the following major parts, namely sensing
unit, processing unit, radio unit and power supply unit. The sensing unit is responsi-
ble for converting the physical measurable properties to digital signal, the processing
unit controls the data flow between the sensing part and the communication part,
the radio unit is responsible for wireless transmission of the sensor data towards the
destination, and the power supply unit controls the power supply between different
parts of the node.

Industrial networks have been significantly dominated by the wired communi-
cation networks. However, the advances in the WSNs have started the shift towards
wireless monitoring and control [9]. IWSNs consist of input/output devices (sen-
sors and actuators) and infrastructure points (routers and gateway) equipped with
radios. Figure 1.1 shows an IWSN topology that allows the host application to com-
municate with the input/output (I/O) devices in the plant field through the routers
and a gateway. Despite the design similarities, there are several major differences
between IWSN and traditional WSN, some of those are listed below.

- Conventional wireless sensor nodes usually have resource constraints i.e., low
  computational capacity with limited RAM and ROM, limited battery life, tiny
  size, etc. These nodes are employed in applications requiring low-power and
  low-throughput. Meanwhile, industrial applications generally need to process
a huge amount of data to trigger timely alarm for upcoming instrument failure [10]. Nevertheless, in wireless communication systems, both bandwidth and energy are limited. This restricts the I/O devices to transmit only useful features after pre-processing the raw data, which requires sufficient computational resources. However, I/O devices with constraint resources are not uncommon in industrial applications [11].

- The transmission power of the conventional wireless sensor nodes is usually low, which results in a short transmission range. However, industrial I/O devices should be able to combat harsh radio propagation environment (because of the presence of heavy machinery in the factory), which often requires relatively high transmission power.

- Conventional WSNs often work in an ad hoc basis by utilizing contention based protocols to communicate with peers [12, 13]. Thus, such networks cannot guarantee high communication reliability whereas the primary goal of IWSNs is to provide reliable wireless communication in the harsh industrial environment to collect sensor data and to actuate machinery whenever necessary.

- A single wireless sensor node in such networks is not expected to provide a high packet delivery ratio. However, collaboratively such networks can deliver useful information about the application domain. It is not uncommon to have a completely dead brunch in conventional WSNs. Such scenarios are not acceptable in IWSNs. To avoid these issues, redundant routing paths are often
utilized in IWSNs.

- Conventional WSNs require a dense deployment to achieve a better coverage by making mesh networks. Typically, several messages have to be exchanged between multiple nodes in order to forward a data packet from a source to a destination in such mesh network. So, the latency of communication is usually quite high in WSNs. Although industrial monitoring applications often do not impose strict latency requirements, control applications involving machines (e.g., robots) that perform discrete actions are highly sensitive to message delays. Hence, IWSNs may require to provide extremely low communication latency (i.e., in the range of 2–50 ms) [11, 14].

- Conventional WSNs utilize multi-hop routing algorithms to efficiently forward sensor data in the mesh network. Packet re-transmissions are often required to improve the system reliability in these networks. Apart from additional latency, this consumes high energy, which quickly drains the battery life of the nodes and makes the overall situation challenging. In addition to these features, IWSNs use redundant paths for communication reliability, which also consumes additional energy.

1.2 IWSN Characteristics

Typical IWSNs have the following characteristics.

1.2.1 System functionality

An IWSN has several functionalities which are required for monitoring and control of the production process. The details of these functionalities are described below.

- Sensing and actuation: The process of converting physical measurable information is called sensing. Actuation refers to a control process by movement.

- Routing: The process of forwarding data to a destination through the network is known as a routing task. Different routing techniques such as graph routing and multipath routing are often used in IWSNs.

- Network management: The network management process includes a set of activities such as formation of the network, node authentication, resource scheduling, route formation and adaptation, network health monitoring and reporting, etc. In general, network management can be classified into the following three categories [15]:


1.2 IWSN Characteristics

- Centralized management: In this approach, a central network manager configures the network, constructs the communication schedule and route according to the requirements of the network devices by using the global network information collected from all the devices.

- Distributed management: In this approach, the neighboring nodes negotiate for management tasks such as communication schedule and route formation.

- Hierarchical management: Such schemes use two layers of management in which the either centralized management or distributed management is used to form the main (mesh) network. In addition, each node in the main network takes the responsibilities of several other subordinate nodes that don’t have enough information about the complete network. In the hierarchical centralized approach, multiple levels of centralized management can be present in which a node belonging to one level acts as a manager for nodes of the next lower level. In the hierarchical distributed management approach, an hierarchy is used by allowing nodes with different capabilities (e.g., managerial device, I/O device). In this case, the I/O devices need to communicate with the corresponding local manager node at first to communicate with the destination in the network. The routing between manager nodes is done in a fully distributed manner.

- Interconnection with the Cyber space: The task of interconnection process is to manage the communication between two separate networks. In industrial applications, the wireless network has to be connected with the wired plant network to send commands from the plant control to the wireless I/O devices and vice versa.

1.2.2 Device classifications

Different types of devices such as I/O device, router, access point, gateway, network and security manager, operate in IWSNs. A brief description on these types of devices are given below:

- I/O device: I/O devices are the sensors and actuators that connect the plant field with the process. The sensors collect the information about physical environment and convert this into digital signal. Actuators covert the digital signals into movement that controls some system by movement. The characteristics of I/O devices are outlined below.
- Energy budget: I/O devices are generally battery powered, however, in some applications, I/O devices can gather energy from the ambiance by utilizing energy harvesters. Such harvester powered I/O devices are becoming popular day by day, which creates a new class of industrial application called *fit-and-forget* technology. However, present-day energy harvesters can only generate sufficient energy for a few packet transfers per reporting cycle of the I/O device. Additionally, the availability of harvested energy typically varies over time in a non-deterministic manner [9, 16, 17].

- Routing: Conventional industrial I/O devices are expected to possess routing and network management capabilities. They may also perform distributed route construction and communication scheduling tasks. However, this depends on I/O device’s resource availability. Should these resources be lacking, the I/O devices cannot perform routing and communication scheduling tasks. In this thesis, by I/O devices, we consider the I/O devices with resource constraints (e.g., battery/energy harvester powered, low computational capacity) that are not expected to be involved in tasks other than sensing and actuation. We treat I/O devices with adequate resources as routers instead (described later in this section).

- Mobility: I/O devices often have little/no physical mobility in industrial applications [11]. However, the radio channel in the industrial environment can be highly dynamic [18].

- Router: Routers are deployed in the network to improve network coverage and connectivity. In conventional IWSNs, the routing role is executed by I/O devices. However, additional routers can be added to allow path diversity to combat plant obstacles. A router does not need to be connected to the process itself. Depending on the application requirement, a router may have the additional features mentioned below.

  - Management capabilities: In some applications, routers can have management capabilities, where they can address the requirements of I/O devices in the local network by allocating the requested bandwidth to them.

  - Rank broadcast: Rank of a router in the network can be defined as a qualifying number that represents its relative position/grade with respect to gateway(s). Rank can be calculated based on different objective functions (e.g., reliability, latency, power consumption, available bandwidth, etc.). Routers may broadcast their ranks so that the resource constrained I/O
devices (if there is any) are able to choose the best possible neighbors efficiently.

- **Gateway**: The gateway aims to interconnect field devices with the plant automation system by exploiting one or more access points. The gateway is responsible for data caching and query processing.

- **Access point**: Access points are attached to the gateway and provide redundant paths between the wireless network and the gateway.

- **Network and security manager**: The network manager handles the network formation, node affiliation, resource scheduling, routing, and monitors network health. The security manager handles security issues (e.g., distributing encryption keys to the network devices).

### 1.2.3 Network characteristics

The scale of industrial wireless networks varies from small to large (one hop to several hops) according to application type. In this thesis, we discuss from a single hop network consists of a few I/O devices for wireless control applications, to a multi-hop network containing hundreds of devices for monitoring applications. In control applications, the required coverage area is typically few hundred square meters with a possibility to have line powered infrastructure nodes. Monitoring applications, on the other hand, may need to cover a multi-square kilometer industrial facility where a few hundred I/O devices powered by batteries/energy harvesters are deployed in a deterministic manner that need to be monitored and be controlled. Line powered infrastructure nodes are often not available in many parts of these networks [19]. We therefore need to ensure global coverage using a wireless, self-forming, self-healing mesh network.

IWSNs are lacking a common physical topology. Different use cases may demand different network typologies in industrial scenarios as discussed below.

- **Mesh topology**: In mesh topology, network devices can establish communication with multiple neighbors to forward data. Based on some objective matrices (e.g., reliability, power consumption, etc.), a network device select parents/children in the network from the available neighbor set. Such topology are used in most of the WSNs to improve reliability, coverage and to reduce burden on central nodes. However, a mesh network often imposes high latency, and therefore might be unfit for critical control applications.

- **Star topology**: In star topology, a central node in the network collect information from all of its children. Thus light weight communication protocols can be
used in these networks. However, star networks are often not scalable, which limits their application in large scale industrial monitoring.

- Hierarchical topology: Hierarchical network topology combines both mesh and star typologies. The backbone network can form a mesh network, whereas each member of the mesh network might form its local star network. Hierarchical typologies are suitable for supporting diverse application requirements of modern industrial automation.

IWSNs utilizing either mesh or hierarchical network topology generally have to support three types of traffic patterns, namely point-to-point traffic, multipoint-to-point traffic, and point-to-multipoint traffic [20].

- Point-to-point traffic: This type of traffic pattern usually used between the devices in the network; i.e., when one device wants to communicate with any other device in the same network.

- Multipoint-to-point traffic: Such traffic is used during the communication between network devices with the gateway.

- Point-to-multipoint traffic: This traffic is used by the gateway to communicate with the network devices.

1.2.4 Data model

- Data generation type: Based of the application scenario, I/O data can be initiated differently in industrial networks. The data generation type can be categorized as either periodic data or event base data.

  - Periodic data: This type of data are generated periodically such as regular sensor data. Timely delivery of periodic data are often necessary [11]

  - Event base data: This type of data are triggered based on events. Such data include alarm, event driven monitoring, etc. and have higher priorities than regular periodic data in industrial applications [11].

- Amount: Most of the network traffic in industrial applications are generated in a periodic manner which requires timely delivery to the destination (e.g., gateway, actuator). The traffic rate varies based on application scenario. In this thesis, we consider different applications where the data traffic rate varies from 1 packet in every 10 ms to 1 packet per second.
1.3 Application requirements of IWSNs

It is impossible to design a single communication protocol that functions both effectively and efficiently for all kinds of IWSN applications due to their diverse requirements. Several standards have been developed recently to address the requirements of industrial applications by providing wireless solutions. Nevertheless, the requirements remain ambitious for most of the wireless technologies. This restricts the application of wireless technologies in monitoring sector while the control sector still relies on conventional wired solutions. This section discusses the most important requirements imposed by the industrial applications such as reliability, latency, security, scalability, energy efficiency etc.

<table>
<thead>
<tr>
<th>Category</th>
<th>Class</th>
<th>Application</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>0</td>
<td>Emergency action</td>
<td>Always critical</td>
</tr>
<tr>
<td>Control</td>
<td>1</td>
<td>Closed-loop regulatory control</td>
<td>Often critical</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Closed-loop supervisory control</td>
<td>Usually non-critical</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Open-loop control</td>
<td>Human in loop</td>
</tr>
<tr>
<td>Monitoring</td>
<td>4</td>
<td>Alerting</td>
<td>Short-term operational consequence</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Logging and downloading/uploading</td>
<td>No immediate operational consequence</td>
</tr>
</tbody>
</table>

Figure 1.2: Application classes as defined by ISA.

- **Reliability**: Industrial applications require extremely reliable network. No parts of the network should be down during the operation period. Most often, redundant network devices are deployed to guarantee reliability in IWSNs.

- **Latency**: The latency requirement varies depending upon the application scenarios. The typical end to end delay tolerance for monitoring applications lies in between few hundred milliseconds to several minutes. For control applications, data deliveries within few milliseconds are often required. Based on the importance and maximum acceptable latency of the applications, the international society of automation (ISA) considers six classes of applications from critical control to monitoring applications as shown in Figure 1.2 [14]. The sensor/process data should be received by the destination in a timely manner in critical control applications, whereas monitoring applications are quite flexible in terms of packet reception latency. Process control applications cover the classes 1-5, while monitoring applications fall under the classes 4-5 [11].
• Security: One of the major requirements of industrial communication systems is to provide secure connection. The network should be protected against internal and external attacks.

• Longevity and energy budget: Most of the equipment in the industry are expensive. To regain the output of these long term investments, industrial equipment are expected to be in service for a long period. In addition, many I/O devices are placed in difficult to reach areas in the factory. Replacing these I/O devices thus often means a labor and cost intensive process, which is unexpected. The energy consumption of I/O devices is negligible when compared to the factory energy consumption. However, energy efficiency is an important requirement for the wireless sensor nodes as these devices are often powered by batteries and replacing these batteries frequently is not a practical solution in an industrial environment. Naturally, efficient wireless communication is essential to guarantee maintenance free operation of these energy constraint I/O devices.

• Scalability: With the advances in the industrial monitoring and control, the number of devices need to be supported in industrial networks are increasing rapidly. This demands for an adaptive network architecture capable of supporting new devices in the network without re-modification. The overall objective is to achieve optimal performance even when the network scales up or the data generation rate increases.

1.4 Limitations of the existing wireless technologies

Wireless communication is a shared media technology. Therefore, one wireless system can be affected by other systems operating in the same and adjacent frequency bands. Due to the license free access, many wireless technologies such as ZigBee Pro [21] and WiFi [22], including the recently developed industrial standards such as WirelessHART [23] and ISA100.11a [24] are utilizing the 2.4 GHz ISM band. As expected, the probability of interference is very high on this band that might affect the communication reliability. ZigBee Pro utilizes frequency agility mechanism to avoid external interference. However, this technique cannot provide robust communications in a dynamic industrial environment. Although WirelessHART and ISA100.11a, do have mechanisms (e.g., clear channel assessment and blind channel hopping) to combat interference arises from other systems, packet losses cannot be avoided completely in these networks when co-exists with other systems [25].
1.4 Limitations of the existing wireless technologies

Traditional WSN standards are designed for applications having soft latency and reliability requirements, i.e., ISA application class 4–5 as shown in Figure 1.2. These standards prioritize energy consumption over the communication latency to improve the network life, while real-time communication guarantee is often required in industrial applications. As a result, these standards cannot address the requirements of industrial control applications [19, 26].

Most of the recently developed industrial systems are build on top of low power IEEE 802.15.4 radio interface, which is basically designed for low and medium data rate (maximum raw data rate of 250 kbps) applications. A typical packet delivery in these systems takes hundreds of milliseconds, which is still suitable for delay tolerant industrial applications (e.g., monitoring application). However, industrial control applications might impose high throughput and strict real-time (milliseconds level latency) communication guarantee, which cannot be achieved by using IEEE 802.15.4 based devices [27]. The dynamic channel allocation scheme of DECT standard\(^1\) seems capable of providing reliable communication guarantee with low latency and high throughput in an industrial environment. The royalty free licensed band of DECT made it interference free from other systems. However, DECT is known for its power hungry behavior and thus become unfit for many industrial monitoring applications. Some attempts have also been made to use WiFi (IEEE 802.11) for sensors networks. Despite providing high data rate, WiFi is not considered as a suitable technology for industrial applications due to its high power consumption and lack of communication reliability that is common in carrier sense multiple access (CSMA) systems [4].

Widely accepted industrial standards such as ISA100.11a and WirelessHART, use a centralized management approach by maintaining a global schedule-matrix to keep track of the cell (timeslot-channel combination) usage of the network devices. Due to this centralized approach the network resources (cells) cannot be re-used in different parts of the network even if they are far from each other. Therefore, these networks are often facing the scalability problem. For instance, WirelessHART and ISA 100.11a can support maximum 50-100 devices in a network [28]. Hence, these systems are not attractive for applications having diverse traffic requirement from dense network deployment, which is the type of network we considered in this thesis.

Most of the condition monitoring and process control applications expect the wireless I/O devices to work for long duration without maintenance. To facilitate maintenance free operation, a wireless sensor node needs a long-lasted energy source. Additionally, replacing batteries are often not a practical solution in an in-

\(^1\) Primarily designed for indoor voice communications.
dustrial environment. Thus, energy-harvesters are becoming popular as an alternative power source of the I/O devices. However, present-day energy harvesters can generate only a small amount of power, which is inadequate for industrial communications. As a consequence, harvester powered I/O devices face many practical challenges in an industrial network [16]. For instance, the amount of harvested energy is subjected to the environment (e.g., availability of vibrations, light) that allows the harvester powered I/O devices to transmit/receive data only when sufficient energy is gathered [29, 30]. Due to the lack of power, these I/O devices might also lose their connection and synchronization from the network frequently. In that case, these devices have to re-join the network to resume their task.

The suitability of the harvester powered I/O devices in industrial networks is largely influenced by the network management approach [9, 16, 31]. The efficiency of the management schemes might vary on the network condition (e.g., static or dynamic). Issues such as node (re-)joining, resource reservation, and response in case of network disturbances (e.g., node and edge failures), are affected by the selection of management scheme. Widely accepted industrial standards such as ISA100.11a and WirelessHART use a centralized network management approach. While successfully addressing many requirements of industrial applications, such as reliability, security and throughput, the central network manager of these standards have several limitations in supporting harvester powered I/O devices. For instance, a harvester powered I/O device cannot afford the communication overhead of the (re-)joining phase in a centrally managed network, which is a time and power consuming process. Moreover, such networks cannot cope with disturbances triggered by harsh industrial environments in a real-time manner. The central system manager (SM) has to fix all such problems (e.g., fixing broken links), which incurs high latency [32]. These problems are further exacerbated as the network scales up.

1.5 Research objective

Based on the problems described in Section 1.4, this thesis aims to address the reliability and energy efficiency aspects of the industrial WSNs. We concentrate on improving communication reliability of the industrial network along with achieving low-latency wireless communication. The thesis also explores how improved network management could be achieved with low overhead and delay. Finally, we try to address the requirements of harvester powered I/O devices in the existing industrial networks without compromising the communication reliability and latency of the regular I/O devices.

The primary research question of this thesis is therefore:
1.5 Research objective

How to provide energy efficient, real-time wireless communication between the I/O devices and the routers in an industrial network while improving communication reliability?

1.5.1 Proposed solutions and the hypothesis

In order to achieve reliable communication with low latency, in Chapter 3 we evaluate DECT based solutions that fulfill the strict real-time communication requirements of industrial monitoring and control applications. The dynamic channel selection scheme of DECT provides reliable performance even in presence of harsh industrial environment.

• Here, we start from the hypothesis that an star network topology can achieve a low latency communication system. We also consider that frequency diversity can improve the communication reliability in an industrial environment.

In order to rectify the drawbacks of the centralized network management approach used by the widely accepted industrial standards, we propose two hierarchical management schemes in Chapter 4. The I/O devices in the proposed schemes, have the ability to dynamically choose the best parents (routers) from their perspective based on different performance requirements (e.g., energy budget, reliability and latency requirement). Thus, the network can better cope with dynamic nature of the harsh industrial environment.

• In order to provide robust and efficient communication between different devices in an industrial network, we start from the hypothesis that various network management schemes can be applied in the network. Generally, these network management schemes can be classified into (i) centralized, (ii) distributed and (iii) hierarchical management approaches. We consider the hypothesis that the distributed and hierarchical management approach can address the dynamic nature of the industrial network.

To make the industrial networks suitable for the harvester powered I/O devices, we propose a fast and energy efficient network joining scheme. The proposed scheme helps the energy constraint I/O devices to re-join the network quickly with low overhead upon disconnected from the network due to the lack of energy. An asynchronous communication scheme is also proposed to help the harvester powered I/O devices to publish their data without joining the network, i.e., without any network overhead. The proposed scheme supports different types of I/O devices (e.g., regular I/O devices with periodic traffic, harvester powered I/O devices with event based traffic, I/O devices requiring high throughout for control applications, etc.) in the same network.
• The hypothesis considered here is that a network joining scheme with low overhead can make the industrial network suitable for harvester powered I/O devices. We also assume that a contention based communication scheme can better address the requirements of the I/O devices with strict energy budget.

1.6 Contributions

Following on the earlier mentioned research objective, the main contributions of this thesis can be listed as the following.

Contribution 1: Identifying the requirements of industrial wireless sensor networks for monitoring and control applications

Industrial applications have different requirements when compared with the application requirements of traditional WSNs. Therefore, it is essential to analyze the requirements of industrial wireless monitoring and control applications before trying to design wireless networks for these applications. In this thesis, we at first discuss different network quality matrices for industrial monitoring and control applications. After this, we give an overview of existing wireless technologies utilized in academia as well as in industries to improve the quality of service (QoS) of the wireless communication in an industrial environment. Part of this work appeared in [31,33,34]:


1.6 Contributions

Contribution 2: Reliable, real-time wireless communication for industrial monitoring and control

In this contribution, we evaluate DECT based WSNs for dense industrial control applications. After this, we present a DECT based solution for wireless control applications by utilizing multiple radios that can improve time response of the network. We also present an industrial channel model capable of recreating the highly dynamic environment of the factory. Part of this work appeared in [33,35]:


Contribution 3: Hierarchical network management approach to support devices with diverse QoS requirements and energy budgets

As discussed before, due to the highly varying application domain, reduced capacity I/O devices are becoming common in industrial applications. A hierarchical network management approach can better support such devices in an industrial environment. In this contribution, we present two hierarchical management schemes to address the requirements of reduced capacity nodes as well as to improve their communication reliability, response in fixing broken links, etc. The contributions presented in Section 4.3 and Section 4.4 have resulted from a joint work with Dr. P. Zand where my focus is on the communication between I/O devices and routers in the local networks while Dr. Zand focused on the management issues in the mesh network. Part of this work appeared in [36–38]:


Contribution 4: Efficient wireless communication for energy harvested I/O devices in the industrial wireless networks

In this contribution, we present an efficient communication scheme for energy constrained I/O devices where our main focus is on reducing management overhead from the harvester powered I/O devices. We introduce a fast network joining scheme that reduces the energy consumption during network joining phase and makes the (re-)joining easier for the I/O devices. The I/O devices in our approach can publish their data more reliably by utilizing spatial diversity in the network. Next, we propose an asynchronous communication scheme for the I/O devices having extremely low energy budget. Part of this work appeared in [39]:


1.7 Organization of the thesis

The remainder of this thesis is organized as follows. Chapter 2 presents the state-of-the-art industrial wireless technologies. Chapter 3 evaluates the communication reliability, latency and scalability of DECT standard for industrial automation. Chapter 4 discusses the service networks for industrial applications and presents two hierarchical network management schemes to address the requirements of modern industrial automation including the resource constraint devices. Linked to this, in Chapter 5, we propose energy efficient network joining and data publication schemes for harvester powered I/O devices. Finally, Chapter 6 concludes this thesis with a summary and by outlining future research directions. The overall organization of the thesis is shown in Figure 1.3
Figure 1.3: Organization of the thesis.
CHAPTER 2

The state of the art of IWSNs

During the past few decades, industrial monitoring and control applications have relied on traditional wired communication systems. However, these technologies are becoming inadequate to fulfill the challenging requirements of the modern industrial applications. Wireless technology, on the other hand, has the potential to revolutionize this industrial automation sector by addressing the limitations of wired counterpart as well as by introducing new applications. While current wireless technologies have put the stepping stones in the wireless monitoring domain, wireless control operations are still fighting for the proof of concepts in the laboratory. This chapter presents an overview of existing wireless technologies commonly used in the industrial automation sector. It highlights the pros and cons of each technology and evaluates the level of performance of these technologies with reference to the requirements of industrial monitoring and control applications. In addition, the mechanisms proposed by academia to achieve real-time and reliable industrial communications are discussed in this chapter. We also describe certain key research problems in IWSNs that have yet to be addressed for successful use of wireless technologies in the industrial monitoring and control applications.

Partially based on:


2.1 Introduction

Industrial applications can be divided into two major classes: (i) monitoring applications and (ii) control applications. Traditionally, both of these applications require extensive and costly wiring throughout the factory. In recent years, WSNs have rapidly revolutionized the industrial automation sector [9, 31]. From wired monitoring and control systems, factories are moving towards complete wireless solutions [40, 41]. These innovations create many new opportunities, such as monitoring of the machine parts difficult to reach (e.g., moving parts), fit-and-forget systems, etc., which wired counterparts have failed to address [42, 43]. Moreover, wireless networks require less maintenance than that in wired networks. Thus usage of wireless technologies in industrial applications can reduce the factory setup and running cost significantly. Nevertheless, many new challenges arise with the inclusion of wireless technologies for industrial automation.

In wireless monitoring applications, the I/O devices usually have to transmit small data packets to the control center with low duty cycle. The communication latency and reliability requirements in such systems are often not very critical. Even few packet losses are tolerable in many applications as this does not cause significant performance loss. Monitoring applications requiring high delivery ratio can utilize different techniques such as packet re-transmissions, as long as delay in packet delivery is not a problem; such a protocol can be found in [44]. So, the main challenges of wireless monitoring and process control applications are the network scalability and the energy consumption of the nodes, as the I/O devices in these applications should last for a long time without maintenance. Moreover, mains powering the nodes or replacing the batteries are not always practical and economical in industrial environment. To address this issue, energy harvesters are becoming popular as an alternative power source for the wireless I/O devices. However, present-day energy harvesters can generate only a small amount of energy, which allows the I/O devices to transmit/receive very limited number of packets per reporting cycle. The amount of harvested energy also varies over time depending on the ambiance of the factory (e.g., amount of light/vibration). As a consequence, harvester powered I/O devices face many practical challenges in an industrial network [16].

Industrial control applications, on the other hand, impose several challenges simultaneously. First of all, the I/O devices must maintain the connections with the control center around the clock to guarantee the minimum delay in the control loop. This timing requirement (communication latency) may vary from few minutes to few milliseconds depending on the application scenario. Applications such as active vibration control in gas turbines used at the power stations, require low latency (mil-
2.2 Overview of the existing wireless communication protocols and standards

Recent developments in ubiquitous computing require robust and reliable WSNs for industrial applications where real-time communications are essential. This section presents an overview of the wireless technologies suitable for industrial applications.

Wireless Interface for Sensor and Actuators (WISA) is a IEEE 802.15.1 based standard, developed by ABB to address the stringent real-time requirements of factory automation [46]. It allows wireless communication between sensors and actuators.

ZigBee Pro [21] is an IEEE802.15.4 based standard which is designed for applications having soft real-time and reliability requirements. ZigBee Pro cannot fight against frequency selective fading channel of industrial environment and thus becomes unsuitable for industrial control applications requiring reliable and timely packet delivery.

WIA-PA is an IEEE802.15.4 based communication protocol for industrial wireless networks that was first developed by the Chinese Industrial Wireless Alliance (CIWA) [47, 48].

In 2008, a media access and networking protocol known as TSMP, has been developed by Dust-networks to provide reliable communication for low power and low bandwidth applications [44]. TSMP utilized time synchronized multi-channel communication to improve reliability in mesh networks. It introduced a novel mechanism that uses different physical channels for every communication instance between a pair of devices in the network with channel hopping and superframe con-
Table 2.1: Comparison between widely used technologies in IWSNs in terms of basic performance parameters.

<table>
<thead>
<tr>
<th>Radio technology</th>
<th>Operating frequency band</th>
<th>MAC/DLL mechanism</th>
<th>Range</th>
<th>Supported number of devices</th>
<th>Max. data rate</th>
<th>Modulation</th>
<th>Network architecture</th>
<th>Operating频带</th>
<th>DECT</th>
<th>ISA 100.11a</th>
</tr>
</thead>
<tbody>
<tr>
<td>WirelessHART</td>
<td>2400-2483.5 MHz</td>
<td>Channel hopping, blacklisting, TDMA</td>
<td>0.75m</td>
<td>outdoors: 300m, indoors: 75m</td>
<td>200kbps</td>
<td>O-QPSK, DSSS</td>
<td>Star, Tree, Mesh</td>
<td>2.4GHz</td>
<td>54MHz</td>
<td>2483.5 MHz</td>
</tr>
<tr>
<td>DECT</td>
<td>1800-1900 MHz</td>
<td>IDEMA-TDD, DCS, FDMA, TDMA-TDD</td>
<td>2m</td>
<td>indoors: 0.75m, outdoors: 5m</td>
<td>250kbps</td>
<td>O-QPSK, DSSS</td>
<td>Star, Mesh, Tree, Mesh</td>
<td>2.4GHz</td>
<td>54MHz</td>
<td>2483.5 MHz</td>
</tr>
<tr>
<td>Zigbee</td>
<td>868-915 MHz</td>
<td>IDEMA-TDD, CMA/CA</td>
<td>90m</td>
<td>indoors: 0.6m, outdoors: 30m</td>
<td>250kbps</td>
<td>O-QPSK, DSSS</td>
<td>Star, Mesh, Tree, Mesh</td>
<td>2.4GHz</td>
<td>54MHz</td>
<td>915 MHz</td>
</tr>
<tr>
<td>WirelessHART</td>
<td>868-915 MHz</td>
<td>IDEMA-TDD, CMA/CA</td>
<td>90m</td>
<td>indoors: 0.6m, outdoors: 30m</td>
<td>250kbps</td>
<td>O-QPSK, DSSS</td>
<td>Star, Mesh, Tree, Mesh</td>
<td>2.4GHz</td>
<td>54MHz</td>
<td>915 MHz</td>
</tr>
</tbody>
</table>

*Only allowed in Europe; only allowed in North America.*
cept. Later, several other IEEE 802.15.4 based industrial standards namely, WirelessHART ISA100.11a and IEEE 802.15.4e-TSCH [49] have derived from the concepts of TSMP protocol.

The WirelessHART standard has been developed by the HART Communication Foundation. WirelessHART is backward compatible with the HART protocol, which is a global standard for wired industrial automation. WirelessHART uses timesynchronized, self-organizing and self-healing mesh architecture.

International Society of Automation (ISA) has developed ISA100.11a standard by specifying new Data-link, Network, Transport and Application layers on top of IEEE 802.15.4-2006 Physical layer to provide robust wireless communication for industrial automation. ISA100.11a uses IPv6 over Low power WPAN (6LoWPAN) protocol in the network layer, which allows IP-based communications over IEEE 802.15.4. The synchronized mesh protocol of ISA100.11a allows every node in the network directly accessible through the Internet. WISA, WirelessHART, WIA-PA and ZigBee Pro do not have the capability to provide such access.

DECT is a digital communication standard developed by the European Telecommunications Standards Institute (ETSI) in early 1988, which is primarily used for cordless phones [50]. Recently developed low energy version of DECT (DECT-ULE) seems to provide prominent services for IWSNs [33].

Table 2.1 shows a comparison of basic performance parameters between widely used technologies in IWSNs. Our surveys in [31] and [33] summarize the main features of TSMP, IEEE 802.15.4e, WISA, ZigBee pro, WirelessHART, WIA-PA, ISA100.11a and DECT, as well as their main strengths and drawbacks.

2.3 Mechanisms used by industrial systems

This section discusses the commonly used mechanisms by IWSNs to improve the performance matrices. The mechanisms include medium access control, network management, channel allocation scheme, spatial diversity, routing etc.

2.3.1 Media access control

Media access control protocols can be categorized into two classes: (i) contention-free (scheduled communication) and (ii) contention-based (event based communication) protocols. Contention free systems are usually achieved by using time-slotted communications, where a particular node get the access of the channel for a short duration known as timeslot to transmit/receive its data. Timeslots are repeated with a fixed duration know as superframe, to allow periodic communication opportunities for the network devices. Such systems are more suitable for supporting real-time
communication, while contention-based systems favor low-throughput, low power applications by accessing the channel when an event occurs and transmit the packet if the channel is free. Contention-based communication protocols, such as CSMA, are thus unable to provide timing guarantees. They are also prone to packet losses by the hidden terminal problem. Time slotted communication can also take place on top of CSMA (slotted CSMA), which can achieve slightly better performance than traditional CSMA. The superframe period can determine several network performance parameters, such as communication latency, energy consumption, and throughput. A short superframe results in faster packet delivery i.e., lower latency and higher bandwidth utilization, however, it consumes more energy, and vice versa. The SM in ISA100.11a networks can determine the superframe period. ZigBee Pro and WIA-PA (in the cluster/star level) also support superframes with different lengths.

Figure 2.1: Combination of contention-free and contention based communications in ISA100.11a.

Most of the industrial standards use contention-free communications to guarantee timely delivery of the data packets. Among those, WISA, WirelessHART, DECT and WIA-PA use fixed length timeslots that do not support any variation in traffic [19]. IEEE 802.15.4e allow the user or SM to configure the timeslot length. This could be advantageous for coping with variable data traffic rates generated in factory automation applications. However, as individual nodes are unable to make autonomous decisions, existing technologies are unable to provide hard real-time guarantees, especially in the presence of variable data traffic. ISA100.11a standard uses a combination of contention-free and contention based communications to support different traffic characteristics, such an ISA100.11a superframe utilizing hybrid hopping patterns is shown in Figure 2.1. Contention free communications (TDMA) are used for regular data communications in ISA100.11a while contention based communications (shared slot in TDMA, or slotted CSMA in the slow hopping period)
2.3 Mechanisms used by industrial systems

for re-transmissions or during neighbor discovery. ISA100.11a also supports configurable time slots. A few industrial systems designed for monitoring applications such as ZigBee Pro, utilize contention-based mechanism, thus become unfit for industrial control applications. ZigBee Pro also allows variable data traffic rate with slotted CSMA.

2.3.2 Channel allocation

Wireless is a shared media technology. As several devices can use the same frequency band, there is always a chance of interference from own system as well as from other network devices operating in the same band [51]. One of the approach used by many wireless technologies to avoid such interference is to share the radio resources intelligently among different users by enabling multi-channel communications [52]. The channel allocation mechanisms in the existing multi-channel wireless systems can be categorized into two major classes namely dynamic channel allocation and sequential channel allocation.

A device in dynamic channel allocation mechanism, tries to chose an unoccupied frequency band for communication. A node listens the ongoing communications in the neighborhood to avoid communication on the busy channels and selects a relatively free channel. In case the communication quality degrades in the selected band, the device tries to find another suitable channel for communication. Such approach has been used in DECT, where it is know as Dynamic channel selection. Dynamic channel allocation mechanism are proven to achieve robust communication in presence of multipath fading and Doppler effect due to mobility. Dynamic channel allocation mechanism is also know as adaptive channel hopping. The nodes following dynamic channel allocation mechanism do not have to change frequency when the channel condition is good. However, they need to collaborate to decide on which channel to switch or listen periodically to keep track of the busy and free channels, both of which can introduce a significant overhead and consume a lot of energy [53]. In WIA-PA the cluster heads and the corresponding subordinate nodes irregularly change their channel on a link-by-link basis in the star sub-network when channel conditions become bad.

In sequential channels allocation mechanism, all the devices in the network changes frequency band in the every communication instance according to a per-determined sequence regardless of the channel quality. Such approach is also know as blind channel hopping. Blind channel hopping are also capable of combating multipath fading. Furthermore, such schemes are easier to implement and energy efficient as the receiver doesn’t have to spend energy in listening before transmitting. One can however, argue its effectiveness in presence of channel selective interference. Such
problems can be addressed by utilizing channel blacklisting technique, as adapted by WirelessHART and ISA100.11a, which is simply avoiding transmissions locally (i.e., by a particular node on the network) on the lossy frequency bands. To implement this scheme, a centralized network manager is essential, who collects all the network statistics including node-based packet loss information on a particular channel.

ZigBee Pro uses a slightly different technique known as frequency agility, where the network channel manager collects interference reports from all nodes. In case, external interference is detected, the network channel manager scans for a better channel and moves the entire network to a new channel. This technique requires network re-formation and thus introduces inconvenient delays. This mechanism is also not capable of handling fluctuating channel conditions. WISA employs frequency-hopping sequences in a way that consecutive hops are widely separated in frequency and the bandwidth of the sub-band is more than the typical coherence bandwidth. WISA uses frame-by-frame frequency hopping by choosing independent channels for original data transmission and corresponding re-transmissions.

2.3.3 Network management

The communication schedule (i.e., superframe length and time slot allocation on it) can either be set by a central SM in the network or the nodes can negotiate their schedules distributively among themselves. WirelessHART, ISA100.11a and WIA-PA use a centralize management technique to maintain real-time communication for high traffic loads, while ZigBee Pro utilizes distributed management. Among the academic works on WSNs, the multi-channel protocols such as TMCP [54] and [55] utilize static channel assignment for communication. However, these protocols cannot provide complete and versatile solutions as ISA100.11a or WirelessHART. Some other MAC protocols such as MMSN [56], MC-LMAC [52], Y-MAC [57], and McMAC [58], which use fully distributed management scheme, face practical issues in real WSNs (e.g., scheduling overhead, high protocol complexity) and eventually become unsuitable for resource constrained I/O devices.

Most recently, an IETF working group named 6TiSCH is formed with an objective to enable IPv6 over the TSCH mode of the IEEE802.15.4e standard [59]. They propose to use a centralized scheduling that works with distributed routing. However, how two separate decision makers (distributed routing and centralized scheduling) can work simultaneously is not clearly described by the group. For centralized scheduling, 6TiSCH propose to support both centralized and hierarchical centralized approaches. In case of centralized scheduler, communication resources (cells) is allocated to each node in the network. On the other hand, in case of hierarchical centralized scheduler, the authority over a block of resources (chunk) is delegated to
the routing devices. The routers can decide locally on how to use those resources to manage their children in the RPL. In the next phase, 6TiSCH also intends to support fully distributed and hierarchical distributed scheduling approaches, although the details is yet to be known.

![Diagram of multipath routing in ISA100.11a]

Figure 2.2: Multipath routing in ISA100.11a

### 2.3.4 Spatial diversity

Spatial diversity is one of the wireless diversity schemes that is employed to improve the reliability of a wireless link often by using two or more antennas. In theory, an independent channel condition can be achieved by placing two antennas (unidirectional) approximately one half wavelength apart from each other, that can help by successfully detecting a signal previously undetected by the other antenna due to deep channel fading [60]. With a directional antenna, the space caution should be higher to achieve independent channel realization. In DECT, such an antenna diversity is utilized on the base-station part to combat multipath fading. However, such technique consumes almost double energy than that of single antenna communication system and consequently become unattractive for battery/harvester powered I/O devices. In WirelessHART and ISA100.11a, spatial diversity can be achieved
by using multipath routing, such a technique to improve packet reception has been proposed in this thesis which is explained later in Chapter 5.

### 2.3.5 Multipath routing

Among the wireless standards discussed in this thesis, WISA and DECT require the network to be deployed in a star/tree topology to ensure real-time capability, while ZigBee Pro, WirelessHART, WIA-PA and ISA100.11a support multi-hop mesh networks. A limitation of star topology is the lack of alternative routes in case the communication between a node and its cluster head is disrupted due to interference. To prevent such problems the SM of WirelessHART and ISA100.11a networks defines multiple alternative paths for each node to reach a particular destination in the network which ensure robust communication in presence of interference and signal blockage. In Figure 2.2 shows multiple uplink and downlink paths from a source to a destination in an ISA100.11a network where each device keeps the addresses of two neighbors for reliability. Although DECT uses a star/tree topology, in case of disturbances, the I/O devices (portables) can establish alternative connection with other suitable base-stations.

### 2.4 Open research areas

While existing industrial wireless technologies are capable of supporting traditional monitoring applications fairly well, significant advances are required before they can be engaged to support harvester powered I/O devices in the industrial networks as well as to be used for time critical distributed control operations. In this section, we highlight some of the key areas need to be addressed to fulfill the requirements of the modern industrial automation.

#### 2.4.1 Reliability

Due to the license free operation, 2.4GHz frequency band has become overcrowded by different wireless system. Widely accepted industrial standards built on top of IEEE 802.15.4 interface such as WirelessHART and ISA100.11a, are also utilizing this facility. However, reliable communication on this band is challenging due to the high external interference probability. Though WirelessHART and ISA100.11a utilizing blind channel hopping and channel blacklisting techniques to combat such interference issue, packet losses are unavoidable in these systems while co-exist with other systems. Thus there are still room for improvement in these standards to better cope with external interference. For instance, adaptive channel hopping can be
applied to dynamically avoid congested channel and spatial diversity scheme can be utilized to recover lost data without additional delay. We propose a spatial diversity scheme in Chapter 5 to improve the communication reliability of harvester powered I/O devices.

### 2.4.2 Latency

By using time division multiple access mechanism to distribute communication resources among network devices, each node get access to a dedicate time slot to transmit/receive data to/from a neighbor. Periodic allocation of such dedicate slots guarantees the real time communication in the system. However, in an industrial harsh environment, packet losses cannot be avoided completely. While communication reliability can often be improved by re-transmitting lost packets, this increases end-to-end packet reception delay. Such delays are not acceptable in industrial control applications.

present-day industrial systems such as WirelessHART and ISA 100.11a, do not support low communication latency, high throughput, and dynamic channel selection to avoid interference. Eventually, robust communication with milliseconds level latency cannot be guaranteed with these systems. Thus, these systems are not suitable for the delay critical control applications while providing satisfactory performance in monitoring and delay tolerant control applications. A star/tree network topology can provide the best timing guarantee required for the control application we are targeting. The DECT standard, preliminary designed for indoor voice communications, can provide reliable communication with low latency required for industrial control applications as evaluated in Chapter 3. However, DECT is treated as a power hungry standard thus might not be suitable for low-power industrial monitoring applications.

Many industrial applications require a mesh topology for increased coverage or scalability. However, a centrally managed multi-hop networks take a long time to gather information about edge failures, which further increases communication latency. Distributed approaches can better manage latency in a multi-hop network. Clearly, one wireless communication protocol cannot fulfill all the requirements of the modern industrial automation sector. Thus, we need new schemes that can cope with these situations while using standard communication protocols. As a response, we propose two network management schemes in Chapter 4 that can provide real-time communications in a multi-hop network.
2.4.3 Network management

Several standards such as WirelessHART, ISA100.11a, WIA-PA are developed to address the before mentioned requirements of industrial applications. Most of these systems use centralized network management approach for resource scheduling and route formation. The robustness of these industrial wireless system highly relies on the precise clock synchronization between network devices due to the utilization of deterministic resource reservation. Although it is easier to implement such management approach, they often fail to react fast in case of channel variation and disturbances as all decisions have to be made by the central SM. This problem is further exacerbated as the network is scaled up, which may result in severe network problems, including high packet loss and long communication latency, increased energy consumption, etc. Moreover, the I/O devices in such networks have to follow complex network joining process and security mechanisms before being able to publish data. Reduced capacity I/O devices (e.g., harvester powered I/O) cannot afford these power hungry procedures due to their limited energy budget. Thus, such I/O devices may frequently lose their connectivity/synchronization when operating in the above mentioned industrial network. Although distributed management schemes have the potential to address these issues, harvested powered I/O devices often do not have the capability to run fully distributed schemes.

We believe, an hierarchical network management scheme can support the reduced capacity nodes in the best possible way where line/battery powered routers can have some management capabilities to allocate communication resources to the reduced capacity I/O devices in the local sub-network. However, such approaches are not adapted by the current industrial wireless technologies. In response, we propose two hierarchical network management schemes namely ISA100.11a* and D-MHR in Chapter 5 to address the requirements of the energy constrained I/O devices.

2.4.4 Energy efficiency

Industrial network devices are expected to last years without maintenance. Although the infrastructure nodes (e.g., routers) often can be line powered, I/O devices have to rely on limited battery or harvested power. Thus, energy efficient communication protocols are essential to have long lasting systems. In traditional industrial systems, similar to the routers, I/O devices also have a lot of management overhead (e.g., periodic health reporting of the links, neighbors health status, etc.) in addition to the regular data traffic, which consumes energy. By reducing some of these management overhead from the I/O devices, the life of these nodes can be
improved significantly. In Chapter 4, we propose two hierarchical network management approaches which can reduce the I/O energy consumption and make the network suitable to reduced capacity I/O devices.

The success of the current industrial technologies utilizing contention-free mechanisms depends on the network synchronization. The routers in these systems broadcast advertisements in a regular interval to allow the I/O devices join the network, get resources and publish their data. Upon powered on, the I/O devices scan the physical channels to detect advertisements. As the I/O devices do not have any clue about the advertisement channels in the beginning, they have to turn their receiver on for a long time, which consume a significant amount of energy. Although an hybrid network management approach solves many problems such as delay to fix broken links, join response from the multi-hop away SM, etc., to support energy constraints I/O devices in the existing industrial networks, the I/O devices still have to scan the physical channels for a significant duration to join the network. To overcome this issue, we propose a fast and energy efficient network joining scheme for the I/O devices that makes the network supportive for the harvester powered nodes in Chapter 4.

2.4.5 Supporting different traffic patterns

With the advances in energy harvesting technologies, some non-critical industrial applications want to use I/O devices only powered by energy harvesters. These nodes may never harvest sufficient energy to spend on idle listening for network joining purpose. To address this situation, complete asynchronous communication might be attractive for the the harvester powered I/O devices to publish their data. That means the harvester powered I/O devices will transmit their data packets by forming ad hoc networks whenever they have energy to transmit. Such contention based communications do not require time synchronization between network devices. However, these systems are not suitable for industrial applications requiring timely packet deliver as they cannot guarantee reliable communication. Thus, a framework is essential which can provide real-time and reliable communications for regular I/O devices in an industrial environment as well as supports energy constraint I/O devices publishing their data in an asynchronous mode under same network infrastructure. Such a scheme is proposed in Chapter 5.

2.4.6 Energy harvesting techniques for IWSNs

Energy harvesting refers to the conversion of any kind of ambient energy into electric energy, typically to fed low-power electronics. An approximate estimation of
Table 2.2: Acceleration magnitude and frequency of fundamental vibration in industrial environment [62].

<table>
<thead>
<tr>
<th>Vibration source</th>
<th>Acceleration ($ms^{-2}$)</th>
<th>Peak frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car engine compartment</td>
<td>12</td>
<td>200</td>
</tr>
<tr>
<td>Base of 3-axis machine tool</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>Blender casing</td>
<td>6.4</td>
<td>121</td>
</tr>
<tr>
<td>Clothes dryer</td>
<td>3.5</td>
<td>121</td>
</tr>
<tr>
<td>Person nervously tapping their heel</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Car instrument panel</td>
<td>3</td>
<td>13</td>
</tr>
</tbody>
</table>

The potential of energy harvesting from some ambient sources, such as solar energy outdoor (15,000 µW/cm³) and indoor (10 - 20 µW/cm³), mechanical vibrations (300 µW/cm³), air flow (360 µW/cm³), is discussed in [61]. However, industrial applications are more likely to use mechanical vibrations given its availability for this type of environment. Table 2.2 provides an indication on the vibration potential energy from industrial environments. Machinery in factory are designed to have minimal vibrations. Thus, it is very hard to harvest energy from such systems during normal operations. On the other hand, increase in vibration often indicates faults in the industry. The nice thing about vibration energy harvesting is that it becomes effective whenever it is important to detect failures by producing significant energy from the increased vibrations, which allows frequent data transfer from the respective sensor nodes and helps to locate the fault soon.

Yet, the potential for vibration based energy harvesting depends on the specific transduction mechanism in place. The main challenge about industrial vibration as source for energy harvesting lies on the impedance matching between the source and the adjacent circuits. This implies that the most efficient extraction is given at a particular frequency for which the circuit can be optimized. However, the frequency content of mechanical vibrations cannot always be predetermined or the energy is spread over a broadband frequency that limits the actual energy availability at particular frequencies. Fortunately, wireless, battery-less industrial condition monitoring systems are already being commercialized where ambient vibrations are used to generate output levels in the range of microwatts to milliwatts. Perpetuum vibration energy harvester (VEH) [63] is such an example, which claims to produce up to 27 mW of usable energy harvested from industrial environment.

This thesis focuses on improving communication reliability and energy efficiency of the resource constraint I/O devices in an networks. A realistic assumption about the capabilities of energy harvesters is essential to design effective protocols for harvester powered devices. Our proposals in Chapter 4 and Chapter 5 use the insight
2.5 Concluding remarks

from the state-of-the art energy harvesting research.

2.4.7 Industrial channel modeling

Every radio signals suffer from free space path loss and shadowing during their travel from transmitter to receiver. These parameters depend on many things such as the geometry of the network, Doppler effect, obstacles etc. A correct propagation model is thus necessary to evaluate a communication system. The movement of machinery, highly reflective materials and electric impulses due to friction or other reasons make it challenging to model the industrial environment properly. To address these issue we conducted a measurement campaign with an ISA100.11a development kit in an industrial environment and validate the channel models proposed in Chapter 3 and 5.

2.5 Concluding remarks

Traditional industrial systems based on wired communication protocols have several major limitations to fulfill the modern industrial application requirements. The rigid network nature lacking flexibility, expensive maintenance requirements, inability to support moving instruments are only few of these limitations from such systems. Wireless technology, however, through its increased pervasiveness, not only can achieve flexible and robust industrial automation but also can create a new class of applications. While present-day wireless technologies are capable of supporting industrial applications where reliability and energy consumption issues are not critical, they still have severe limitations, especially when time critical reliable distributed control operations are concerned or energy constrained nodes have to be supported without sacrificing the quality of service. In the next three chapters, we discuss such issues and present novel approaches to support the requirements of factories of the future.
Wireless sensor networks have revolutionized the industrial automation sector by enabling wireless sensing and control to the machine parts where wiring is impossible. However, new challenges in terms of communication reliability, latency, throughput and network scalability, appear with the advances in the industrial wireless automation. Existing IEEE 802.15.4 based industrial standards are found inadequate to support many of these demanding situations. Digital Enhanced Cordless Telecommunications (DECT), a voice communication standard, seems to support many of the requirements of modern industrial wireless monitoring and control networks. In this chapter, we evaluate the performance of DECT for industrial monitoring and control applications and found that it can cope with the limitations of existing industrial standards. The dynamic channel selection (DCS) scheme of DECT can elegantly handle dense WSNs by allocating communication channels with excellent quality and minimum delay. DECT based wireless networks for control applications can also maintain excellent communication reliability between the I/O devices and the control center with low latency even in a harsh industrial environment.

Partially based on:


3.1 Introduction

Recent developments in wireless sensor networks (WSNs) help the industries to get rid of wires by enabling wireless communication between the field network and the plant network. Along with many potentials, these technologies also bring a set of challenges, among which communication reliability is one of the most important aspects that the industrial applications might not compromise with. In industrial monitoring applications, the I/O devices are supposed to send information consisting of few bytes to the gateway occasionally; i.e., the duty cycle of the I/O devices used in these applications is very low. Extremely reliable wireless communication is not generally required for monitoring applications. However, wireless monitoring networks often face challenges in terms of network scalability and energy efficiency. Industrial control applications, on the other hand, require real-time communication guarantees. Thus, communication reliability and latency are critical in control applications. High throughput is also necessary in large control systems.

The goal of this chapter is to identify a suitable radio technology and evaluate its performance for the scenarios where extremely reliable communications are essential along with high throughput and low communication latency. Naturally, widely used IWSN standards such as WirelessHART and ISA 100.11a, come first in consideration during the selection. Most of these recently developed industrial standards are built on top of IEEE 802.15.4 interface which uses the unlicensed 2.4 GHz frequency band for communications [51]. The same frequency band is also used by many other devices in homes and offices such as, WiFi, Bluetooth, microwave ovens etc. As a result, communication channels in this band encounter interference not only from its own system but also from other neighboring devices operating in the same band. So, the chance of having interference in this band is quite high. Moreover, IEEE 802.15.4 standard is designed for low and medium data rate (maximum raw data rate of 250 kbps) applications. As a consequence, existing industrial standards become unfit for applications requiring high throughput. In addition, WirelessHART and ISA 100.11a are designed to support maximum 50-100 devices in the network [28]. However, thousands of I/O devices should to be supported in modern industrial applications. Thus, the radio resources have to be shared intelligently among different users by enabling multi-channel communications [52]. A typical packet delivery takes few hundred milliseconds in a WirelessHART or ISA 100.11a network. Eventually, reliable communication with milliseconds level communication latency cannot be guaranteed in the existing industrial standards, which are key requirements in many industrial applications [27]. Thus, these technologies are not

1 Time Synchronized Mesh Protocol (TSMP) implemented in WirelessHART claims to achieve 99.9% re-
suitable for the delay critical control applications while providing satisfactory performance in monitoring and delay tolerant control applications. Clearly, the existing wireless communication standards of cannot fulfill many requirements of the modern industrial control systems. Such a study is conducted in [31] by addressing the limitations of the existing radio technologies in industrial monitoring and control networks. Thus, modern WSNs stand in need of a standard/protocol which can provide robust and real-time communications with sufficiently long transmission range, high throughput and low energy consumption.

The robust communication performance we are targeting in a harsh industrial environment, seems achievable with a digital communication standard developed by the European Telecommunications Standards Institute (ETSI), namely DECT [64–69]. Thus, we use DECT as a reference point for this chapter. DECT is known for its power hungry nature, which makes it unattractive for battery powered I/O devices. However, recently developed, DECT-ULE which is the energy efficient version of DECT standard, gives the impression to support the high density industrial monitoring networks with relatively low power consumption. To follow on this, we evaluate the performance of DECT-ULE in a dense WSN in this chapter. After this, we evaluate DECT for low latency industrial control systems, where highly reliable communication links should be maintained with low latency.

Before going into the details, we briefly explain the features and operating principles of DECT and DECT-ULE in Section 3.2. Section 3.3 presents the evaluation results for industrial monitoring applications. The evaluation results for industrial control scenario are presented in Section 3.4, and finally we conclude this chapter by outlining future research plans in Section 3.5.

### 3.2 DECT and DECT-ULE

In Europe, DECT PHY layer occupies the licensed and royalty free block of radio spectrum from 1880 MHz to 1900 MHz.² DECT has a centralized system, where the fixed part (FP) provides wireless communication to the portable parts (PPs) by broadcasting beacons which contain system and access right information. An FP may comprises several radio fixed parts (RFPs). The RFPs are typically connected between themselves through wires that maintain high synchronization. DECT standard divides its bandwidth into 10 radio carriers using the frequency division multiple access (FDMA). On top of that, the time division multiple access-time division duplex (TDMA-TDD) structure provides 12 time slots for up-link communications

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² In the rest of the world it has different frequency bands based on location.
and 12 time slots for down-link communications per carrier with a frame duration of 10 ms. As a result, DECT has 240 physical channels for communication during a 10 ms frame. However, a RFP (base station) with single transceiver can only handle 12 simultaneous connections as the radio cannot switch between frequencies in a particular time slot [50]. A typical DECT frame on an RFP is shown in Figure 3.1, where the RFP is busy on 2 channels (marked in Blue and Green colors). The RFP cannot communicate on the channels marked in Grey color which are so-called blind channels. The channels marked in White color are the free channels on that RFP.

![DECT frame](image)

**Figure 3.1: DECT frame**

DECT system uses bearers to provide connection-oriented and connection-less services. The MAC layer of DECT creates bearers from the data packets it sends and receives from the PHY layer. DECT uses four different types of bearers, those are simplex, duplex, double simplex, double duplex. If a single slot in PHY layer is allocated for a service, the bearer is called simplex bearer. The bearer where one slot in down-link and another in up-link have been allocated for a service is known as duplex bearer. These two slots are allocated in the same RF carrier with 12 slots spacing in between. This type of bearers are used in DECT voice communication most frequently. Double simplex bearers have the same structure as duplex bearers except the both slots are used in the same direction, i.e., either in down-link or in up-link. This type of bearers are usually used for data streaming from base stations to the mobiles and vice versa. These bearers have to be guided by a duplex pilot bearer. Double duplex bearers is a combination of two duplex bearers in two RF carriers [70].

A single DECT RFP can support hundreds of PPs. So by using tens of those, thou-
sands of PPs can be supported in a network. The data rate of DECT is much higher than those of WirelessHART, ISA 100.11a or ZigBee. The raw data rate of DECT is 1152 kbps, which is suitable for data streaming as well as for low data rate applications. DECT also provides long radio range (typically up to 75m indoors and up to 300m outdoors) due to the permission of high transmission power. Complex mesh networking thus can be avoided, even if the network is large and dense. DECT-ULE is the new version of DECT which has low energy consumption due to its capability to go into long sleep mode without losing synchronization. Thus a DECT-ULE radio attached on an I/O device can operate years (typically 5-10 years) on a single battery. In standby mode, a DECT-ULE chip draws about 5 mA current at 3.3 V power supply. As, all the features of DECT-ULE are almost same as those of DECT, the results obtained in this paper using DECT-ULE will be same with DECT also, unless mentioned.

The operating principle of DECT is briefly explained below.

### 3.2.1 Fixed part beacon and the portable locking procedure

Every radio network from a single hop to multi-hop system, broadcasts beacons to provide the PPs not only the access right information but also the system information, paging information, etc. To place the beacons, FPs have to select suitable channels. The FPs and PPs in DECT system maintain the same protocol for channel selection, "listen before transmit". After powered on, RFPs scan the physical channels to create a list of least interfered channels. The channels on which the RFP receives low RSSI or can’t detect anything are known as least interfered channels. The RFPs then place their beacons on one of those. These channels are known as locked channel. In Figure 3.1, the corresponding RFP broadcasts its beacons on RF carrier 5 and slot 5 marked in Blue color. The PPs have to listen to the RFPs on one of the locked channels to get locked in the system. In DECT, every RFP broadcasts at least one beacon in each frame. As a large amount of information is suppose to broadcast throughout the network using the beacon, this information has broadcasted in several frames after divided into several parts. As a result, the contents of the beacons of a particular RFP at every frame may not be identical. The MAC layer of DECT controls this multiplexing, the details are beyond the scope of this paper [50].

In DECT, 16 frames create a superframe (frame number 0 till 15). Among many other information, the access right information is placed in every frame while the system information is only broadcasted in frame 8 of a superframe. When a PP has been switched on, it tries to receive a beacon from the FP. If beacons from several RFPs have been received by a PP, it selects the beacon of the RFP from which it gets the strongest received signal strength indicator (RSSI). The PP then checks the access
right information to determine whether or not it has an access on that system. If
the PP can decode the access right information successfully, several messages are ex-
changed to lock the PP into the system. After receiving the system information from
the beacon the PP can achieve the superframe synchronization as this information is
only placed in frame 8 of a superframe.

The RFPs change the channel for beacon broadcast in a regular interval even if
there is no interference. In frame 8 of every superframe, the FP declares selected the
RF carrier and slot number of future locked channel for next superframe. So, the PPs
have been notified about any change in locked channel beforehand. This enables the
PPs to switch the locked channel without losing the synchronization.

3.2.2 Paging

If the FP wants to make a connection with a PP (usually a connection has always
been initiated by the PPs in DECT system), it sends paging messages over the beacon
throughout the network. The PP in question is then know that there is a request for
connection waiting for it. The paging information is typically placed in frame 0 of
a superframe. By doing so the PPs only need to wake up once in every superframe
to check for potential connection requests after getting locked into the system [70].
This helps the PPs to save energy. In case of DECT-ULE the PPs can go into sleep
mode for a longer period (up to 20 seconds) than the allowed maximum sleep time in
original DECT (1 to 4 superframe duration, i.e., 160 milliseconds to 640 milliseconds).
However, this will increase the latency. During this long sleep period, the DECT-ULE
chip draws a very small amount of current (typically 3 µA, maximum 5 µA) which
enables the wireless I/O devices to last for years on a single battery [71]. An external
clock is used in DECT-ULE chip to trigger a force wake-up if necessary. This allows
the PPs to react fast and communicate with the FP in case of emergency.

If there are a lot of paging in the system, the paging information can also be
placed in the even numbered frames. In those cases, this is notified through the bea-
con of previous even numbered frame. So, the PPs know in advance that they have
to awake again in next even numbered frame to check for potential connection re-
quests. A connection has only been made if the PP accepts the request, if not the
connection will be abandoned. In practical systems paging information is generally
broadcasted 3 times, this reduces the chance of missing a call by the PPs. The con-
nection can be ended by placing call releasing bearers when either parties (PPs) press
the end button.
3.2.3 Dynamic channel selection (DCS)

In a DECT network, the portable parts (PPs) drive the connection setup, handover and many other major protocols of communication in DECT standard, which is unique among other communication standards. To select the best channel for connection setup, all the PPs keep a list of suitable channels which is updated periodically. DECT system consider a frame length of 10 ms, which is again divided into 24 time slots. Generally, a PP uses only 2 (one for uplink, one for downlink) of these slots for communication in a frame. Rest of these slots can be utilized for idle listening, which is useful to create channel selection list. PPs are listening to the radio fixed parts (RFPs) on the free channels constantly when active and occasionally when idle. The channels in which the PPs receive high RSSI are considered busy and the channels in which the PPs don’t receive anything are the quietest channels. According to the RSSI, the PPs sort the channels into 12 levels. Level 1 contains the least interfered channels, i.e. the channel whose RSSI is less than the receiver sensitivity (typically -93dBm) and level 12 contains channels whose RSSI is greater than -33dBm. As the channels in level 12 are the most interfered ones and no connection should be requested on those channels. All other channels are sorted into 10 levels in between with 6 dB interval. A typical channel selection list on a PP is shown in Figure 3.2. If a PP wants to initiate a connection in a system on which it has granted access beforehand, at first it selects the strongest RFP. Then it requests for a connection on a channel from level 1. In case of channel unavailability in level 1 other channels in higher levels up to level 11 can be tried to make a connection in a hierarchical order. After selecting a channel, the PP has to check the RSSI of that channel in next

![Figure 3.2: Channel selection list](image)

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3 The RFP from which it receives the beacon with the highest RSSI.
two frames before finally selects the channel for connection setup. If the RSSI of the channel does not decrease 12 dB from the initial value, the PP sends a connection request on that channel. The RFP assigns the channel straight forward if it is free. It may happen that more than one PPs requested for a connection on the same channel, so a collision may occur at the receiver of the RFP. In this case no PPs may get an acknowledgment from the RFP, so the PPs have to select another channel for the connection. The phenomena when a PP places a connection request on a channel but the channel cannot be allocated is known as channel selection failure [72]. In case of channel selection failure, the PPs may try another 5 suitable channels in the same RFP to setup the connection, if failed the next two strongest RFPs can be tried using the same procedure. If no connection can be made after trying 3 strongest RFPs, the connection will be dropped [73].

Again, in case an RFP doesn’t have any free channels to accept further connection requests, the RFP can send this information on its beacon. Then the PPs belong to that RFP know that the RFP is unable to take further connection requests even though that is the strongest RFP for those PPs. However, in that case the PPs under question can direct their connection requests to the respective 2nd strongest RFP instead.

3.2.4 Connection supervision and handover

As long as the connection exists, each PP monitors the RSSI from all RFPs, the RSSI on each channels and the communication quality (i.e., message error rate) on both up-link and down-link. If at the time this monitoring, the PP finds another RFP whose RSSI is at least 10 dB higher than that of the present RFP, it initiates a handover procedure. The handover procedure is similar to the connection setup procedure except the PP maintains two simultaneous connections during the handover procedure [73].

Any signal whose power is greater than the receiver sensitivity can be detected by a receiver. Nevertheless, a minimum SINR should be maintained to successfully decode a received signal. The interference in DECT mainly occurs due to the use of same channel by different pairs of RFP and PP, which are in the communication range of one another. The interference is calculated on a PP for a particular channel by summing up the received power from two other RFPs (if there are any) [74]. The PPs continuously check the SINR of the channels on which they are communicating. If a particular link becomes bad, the PP initiates a handover process. Most of the time, the handover has been done seamlessly.
3.3 Evaluation for industrial monitoring applications

The nature of WSNs is quite different than telecommunication networks. It varies in geometry, density, traffic, connection duration, data size, etc. Deployment of I/O devices in an WSN typically depends on the application. Most of the times, I/O devices are dropped in an ad hoc manner. In this evaluation, we consider a dense WSN in a car manufacturing industry where different types of I/O devices are deployed to gather different data and to control different machinery. Some I/O devices are employed to monitor the vibration signatures of different machines and control those wirelessly, some collect the temperature readings, some sense the pressure, some control the lighting, etc. In our network 25 infrastructure nodes (RFPs) are placed systematically in a 100 m X 100 m area and 1000 I/O devices (PPs) are distributed uniformly throughout the area as shown in Figure 3.3. The I/O devices are equipped with radios and capable to communicate wirelessly with the RFPs. The physical connection through wires provides the RFPs high synchronization, while the I/O devices get synchronize through the beacons.

In DECT systems intended for voice communication, the traffic generation is usually modeled according to Poisson’s distribution. When a voice connection has been initiated, it is expected to last for a while (typically, few minutes). The connection duration in such networks is modeled as an exponential distribution by the researchers in [69,75]. On the other hand, in wireless sensor networks, the traffic generation pattern can be very diverse. Some I/O devices only initiate a connection if those detect
an event, while others are expected to send a message in a regular interval. Most frequently, the I/O device data consists a few bytes so the connection duration is quite small (typically 2 DECT frame duration). However, applications where I/O devices are deployed to stream a large amount of data, the connection duration can be high as voice call duration. As a result, the conventional models of traffic generation and duration of connections may not be suitable here. Up to 40 Bytes of user data can accommodate in one physical channel of a DECT frame, which allows maximum throughput of 32 kbps [50, 70]. To support high throughput, more than one time slot allocation may be necessary for a particular communication link. Therefore, to cope with these scenarios, we introduced three parameters: the number of initiated connections in every frame, \( N_c \); the duration of the connection, \( T_c \) and the data size of the connection, \( D_c \) (i.e., the number of slots required in each frame for the connection as this is directly related to the required throughput).

Before initiating a connection, each I/O device has to be locked into the DECT system through a suitable RFP from which it receives beacons with the highest RSSI. Suppose, \( N_c \sim U(0,n) \) connections can be initiated in the network at a particular frame. These connections are generated from different I/O devices, among which some may request a channel to the same RFP. We evaluate the performance of DECT under different traffic density. The commonly used unit of traffic density, Erlangs to evaluate the performance of voice communication networks, does not make clear sense in case of WSN simulation. Thus, we choose numerical scale to simulate low and high network traffic (i.e., by varying the value of \( n \) in the distribution \( U(0,n) \)) instead of using Erlangs scale. \( n = 10 \) has been set to simulate a low traffic network, while \( n = 100 \) has been set to simulate the high traffic case. The I/O devices have to select a channel which is relatively quite to place a connection. For this purpose, DECT standard uses the DCS mechanism explained earlier. We also consider the channel selection list of the I/O devices (PPs) be updated in every 10 seconds (i.e, 1000 frames). To provide a diverse nature in connection duration, we consider \( T_c \) (expressed in DECT frame duration) as a random integer generated from the following

---

4 For simplicity we represent the duration of a connection with DECT frame duration.
5 In this work we assume that 1 slot is necessary to support a throughput 0-32kbps, 2 slots are necessary to support a throughput 32-64kbps, and so on.
6 The reduction in channel update time might increase the power consumption.
3.3 Evaluation for industrial monitoring applications

probability distributions,

\[
P(T_c = T_{c1}) = 0.8; \ T_{c1} = 2
\]

\[
P(T_c = T_{c2}) = 0.15; \ T_{c2} \sim U(3, 10)
\]

\[
P(T_c = T_{c3}) = 0.03; \ T_{c3} \sim U(11, 20)
\]

\[
P(T_c = T_{c4}) = 0.02; \ T_{c4} \sim U(21, 50).
\]

Again, the data size, \(D_c\) (required number of slots in a DECT frame) is also considered as a random integer created from the following distributions,

\[
P(D_c = D_{c1}) = 0.95; \ D_{c1} = 1
\]

\[
P(D_c = D_{c2}) = 0.05; \ D_{c2} \sim U(2, 6).
\]

In our simulation, we consider allocating duplex bearers for the connections whose data size requirement is below 7 slots and for the rest of the connections we allocate simplex bearers. We also introduce periodic connection generations in the network as most of the I/O devices in WSNs are deployed to send a message in a regular interval. If I/O device \(x_i\) requests for a connection in frame \(p\) and the period of reporting is \(q\) frames, then I/O device \(x_i\) will attempt for a connection establishment again in frames \(p + q, p + 2q, \ldots\). If a connection request from I/O device \(x_i\) which is initiated in frame \(p\) is dropped after following the connection setup procedure, the data size will be increased during the next expected attempt (i.e., during frame \(p + q\)) as the I/O device has to send the old data also. This pattern will continue until the data size is equal to the maximum allowable slots in a base station. After that, the connection will be dropped permanently as it is not possible to place such a connection. As a consequence, the corresponding data cannot be recovered. We define this phenomena as lost connection. According to DECT standard, maximum 24 slots (22 simplex bearers guided by a duplex pilot bearer) can be allocated for a particular connection.

Propagagation model

Every radio signals suffer from free space path loss, shadowing and fading during their travel from transmitter to receiver. These parameters depend on many things such as the geometry of the network, Doppler effect, etc. A correct propagation model is thus necessary to calculate the SINR of a channel. In this simulation, we use the ETSI propagation model of path loss, which can be represented as follows.

\[
L = L_0 + 10\alpha \log (d) + KL_f + L_s + F, \quad (3.1)
\]
where $d$ is the distance between the RFP and the PP in m, $L_0$ is the unit loss in dB (i.e., the loss after 1 m distance), $\alpha$ is the attenuation factor, $K$ is the number of interposed floors, $L_f$ is the attenuation per floor in dB, $L_s$ is the shadowing factor in dB, $F$ is the multipath fading margin in dB. We set $L_0 = 30$ dB, $\alpha = 3.5$, $K = 1$, $L_f = 15$ dB, and $L_s \sim U(-10, 10)$ dB for our simulation. We assume the I/O devices are deployed indoors. Generally, I/O devices are static in industrial environment. However, movement of the machinery can trigger multipath effect. Considering multipath fading for 99% I/O devices, a fading margin of $F = 20$ dB is considered. However, with antenna diversity turned on, we can consider $F = 10$ dB. To setup and maintain a connection with bit error rate (BER) less than $10^{-3}$, a minimum SINR of 21 dB should be maintained [74,76,77]. During the SINR calculation, a transmission power to 23 dBm (according to DECT-ULE standard) and a background noise floor of -100 dBm are considered.

3.3.1 Results and discussion

The novelty of the DECT-ULE system lies in its DCS mechanism. Therefore, to evaluate the performance of DECT-ULE in a dense WSN, we mainly have to evaluate the resource allocation method (i.e. DCS) of DECT. As a performance checker, we analyzed the mount of channel selection failure, SINR of the connections, average load per RFP and the connection setup delay of the network, which are explained below.

3.3.1.1 Channel selection failure

The number of connection requests and the number channel selection failure per frame are compared in Figure 3.4. In case of low traffic (maximum 10 parallel connection initiation), the number of connection requests is almost constant throughout the frames. In most of the frames, there was no channel selection failure. On the other hand, in high traffic case (maximum 100 parallel connection initiation), we see a specific pattern of connection initiation. During frame 1 to 40, most of the connections have been initiated; in some cases the number of connection attempts is almost 20 times higher than that of in low traffic case. Besides, during frame 40 to 100, almost no connection request has been placed. The high connection density pattern is again continued during frame 101 to 140 and so on, due to the periodicity of the connection generation. As mentioned earlier, up to 100 new connections can be initiated per frame in high traffic case, which some times can trigger around 200 connection attempts (including the repeated connection requests of the PPs which have denied access of a channel in previous frames). All the 1000 I/O devices of the network can finish requesting a connection within first 15-30 frames, this is the main reason of
3.3 Evaluation for industrial monitoring applications

Figure 3.4: Initiated connection vs channel selection failure for different traffic densities.

this specific pattern of connection initiation. The I/O devices which failed to select a channel to place a connection in a particular frame, can reattempt to place the connection during next 17 frames. As a result, we see there are still some connection attempts up to the frame 40. Total 1.42% of the connections fail to select a channel in low traffic case, while 17.05% channel selection failure is observed in high traffic case. Although some I/O devices are failed to select a channel during first few frames, most of those are able to setup the connection in next frames by reattempting for the connection. This results in a final 0.0442% lost connections in low traffic and 0.4173% in case of high traffic. Therefore, it can be said that DECT standard can handle the ad hoc traffic in wireless sensor networks elegantly.

3.3.1.2 SINR of the channels

In DECT, a particular I/O device receives interference on a channel when the same channel has been used by other RFP-I/O device pairs in range. The SINR on a communication channel used by a I/O device-RFP pair may have different values in different frames during the connection period, as the other RFP-I/O device pairs may or may not use the channel in question in every frames during the connection period. In our simulation, we checked the SINR of every channels used for communication.

---

7 Considering the I/O device can find a signal from at least 3 RFPs and in each RFP it has at least 6 free suitable channels, the actual number of reattempt for a connection can be lower for some I/O devices.

8 The data of these connections cannot be recovered.
in every frames during the connection period because a handover may take place if the SINR falls below the threshold. Again, the SINR of a channel during a frame may be different in down-link and up-link as RFPs may also have simplex channels along with duplex channels. However, we ignore such possibilities for simplicity.

![Figure 3.5: The cdf of SINR for different traffic densities.](image)

and consider the same SINR for down-link and up-link. In our simulations, almost all the channels (99%) used for the connections are found capable to maintain the minimum required SINR (21dB marked by Green line) both for low and high traffic density cases, which can be visualized in Figure 3.5. Most of those (>90%) actually have quite high SINR that can maintain excellent connection quality. As a result, the handover request due to the bad channel quality can be ignored. In the first part of Figure 3.5, the channels for the high traffic case have slightly lower SINR than those in low traffic case. The reason is the ad hoc connection initiation pattern of WSN explained in Section 3.3.1.1. As, a lot of connections have been initiated during the first few frames, the chance of getting co-channel interference is higher. Again, the high traffic case achieve higher SINR in the later part of the cdf comparison curve as there are few connection attempts during frames 30-100 which decreases the probability of co-channel interference.

### 3.3.1.3 Average load per RFP

In Figure 3.6, the average load per RFP is shown for both low traffic and high traffic case. The average load per RFP is calculated by counting all the used channels for
3.3 Evaluation for industrial monitoring applications

communication by all the RFPs in a particular frame and taking the average among all the RFPs. In case of low traffic, the average load per RFP is varying between 1-2 channels. This is far below to the maximum allowed traffic per RFP. So there is still enough room for new connections in the network. In high traffic case, the

![Figure 3.6: Average load per RFP vs frame for different traffic densities.](image)

average load per RFP has some peaks due to the special connection initiation pattern showed in Figure 3.4. Some times, the peaks reach near the maximum load capacity (i.e., 12 allocated channels per RFP). Although, the average traffic per RFP is really high for the later case, most of the channels used for the communication are able to maintain excellent quality, which is shown earlier in Figure 3.5. This again justify the robustness of DECT in high traffic WSNs.

3.3.1.4 Connection setup delay

Another important issue in any communication network is the latency, which has been overlooked in most of the WSN applications. However, we have to consider this issue for many recently envisioned WSN applications where real-time communication should be guaranteed. In Figure 3.7, we analyzed the connection setup delay for both high traffic and low traffic scenarios. In both cases, we observe that more than 90% connections have been established without any delay, i.e., in the same frame where the connection setup request has been sent. Only a few connections

\[\text{In practical systems PPs generally scans two future frames after selecting a channel for connection setup. In our simulation we ignore this part.}\]
(less than 1% in low traffic case and less than 2% in high traffic case) require more than 2 repeated connection requests to find a suitable channel for connection setup. This really fits with the requirements of previously mentioned applications.

### 3.4 Evaluation for industrial control applications

In industrial control applications, the reliability of the wireless communication is more important than the number of I/O devices supported in the network. In this evaluation, we consider an IWSN where different machinery of a factory are wirelessly controlled from a control room. I/O devices are attached to machines to gather different parameters such as vibration signatures, temperature readings, pressure, etc. and to actuate these machines according to the command of the control room. Suppose, DECT transceivers are attached on the I/O devices to communicate wirelessly between the machines and the control room. In our network the control room collect I/O data through 10 RFPs, which are placed systematically in a $100 \text{ m} \times 100 \text{ m}$ factory and the machines are uniformly distributed in that area as shown in Figure 3.8. A number of I/O devices (30-120) are attached to those machines. The RFPs are highly synchronized due to the wired connections, while the I/O devices get synchronize through the beacons. A total 50 random networks have been simulated for each set-up in MATLAB to evaluate the performance of DECT in this scenario.
3.4 Evaluation for industrial control applications

Figure 3.8: A sample DECT network for industrial control with 10 RFPs and 60 I/O devices.

Traffic pattern

Maximum 120 I/O devices (with 100% duty cycle) are considered in our simulation because with 10 base stations we can keep at most 120 continuous connections in a DECT network. However, this doesn’t limit the capability of DECT systems to support a large network with hundreds of I/O devices. The readers are refereed to [33], for results in such environment where DECT handles a dense network elegantly.

Machinery should be continuously monitored and controlled with minimum delay if needed in an industrial network. So, when an establish connection with the RFP, it expects to last for a long time. As a result, the conventional models of traffic generation and duration of connections are not be suitable here. We consider that upon start up the I/O devices attempt to make connections with the RFPs one after another and suppose to maintain their connections for a long time. For our evaluation, we run the simulation for a long duration. However, for better visualization, we plot the results of first 2000 DECT frames for every I/O device. A certain number of reattempts for channel selection can take place if a suitable channel is not found, after that the connection will be considered as lost. We do not attempt to re-establish a connection if a I/O device loses its connection during any time after it established successfully.
Propagation model

In this work, we use the same ETSI propagation model used in the evaluation of DECT for dense industrial monitoring applications, which can be represented as follows [78].

\[ L_t = L_0 + 10\alpha \log(d) + KL_f + L_s + F, \]  

(3.2)

where, \( L_t \) is the transmit power in dBm, \( L_0 \) is the unit loss in dB (i.e., the loss after 1 m distance), \( \alpha \) is the attenuation factor, \( d \) is the distance between a I/O device and the respective RFP in m, \( K \) is the number of interposed floors, \( L_f \) is the attenuation per floor in dB, \( L_s \) is the shadowing factor in dB, \( F \) is the multipath fading margin in dB. To replicate an indoor office environment for our simulation, we set \( L_0 = 30 \) dB, \( \alpha = 3.5 \), \( K = 1 \), \( L_f = 15 \) dB and \( F = 10 \) dB (considering 99% I/O devices have multipath with antenna diversity on).

The goal of this work is to evaluate DECT for harsh industrial environment. As a consequence, we have to modify the channel model accordingly. Generally, the deployed I/O devices are static in industrial environment, so no Doppler effect is considered in our simulation.

Typically, for indoor home/office environment the shadowing effect is modeled as an uniformly distributed random number and the value of shadowing effect is considered as a constant for a transmitter-receiver pair during the whole connection period. However, in factory environment, the movement of the machinery, highly reflective materials and electric impulses due to friction or other reasons can trigger time varying shadowing effect typically known as temporal fading. Tanghe et al. conducted a measurement campaign to model the large scale and temporal fading in the small industrial environment [18]. They modeled the large scale fading as a log-normal distribution and the temporal fading as a Rician distribution with mean 12.3 dB and standard deviation of 2.4 dB/sec to 15.5 dB/sec. Similarly, we model the shadowing effects as a random variable over time for a particular transmitter-receiver pair to obtain industrial channel environment. For simplicity, we consider Gaussian distribution for time varying shadow fading. More explicitly, a random number is selected from a uniform distribution at first as proposed by ETSI for indoor DECT channels [78]. Then the selected random number is used as the mean of a Gaussian with a particular variance to generate the time varying nature of shadowing effects during a particular connection. The value of this variance is varied from \((1\text{dB}/10\text{ms})^2\) to \((3\text{dB}/10\text{ms})^2\), to simulate a moderate to drastic shadowing effect of the industrial environment.\(^{10}\)

\(^{10}\) 10 ms comes from the DECT frame, i.e., in every frame during the connection we have a sample for shadowing.
Mathematically, $L_{s,t} \sim \mathcal{N}(\mu_s, \sigma^2)$ dB, where $\mu_s = \mathcal{U}(-10, 10)$ dB. The industrial channel with $(1\text{dB}/10\text{ms})^2$ shadow fading variance is considered as the reference for our simulation.

To set-up and maintain a connection with acceptable bit error rate (BER) (typically, less than $10^{-3}$), a minimum SINR of 21 dB should be maintained in DECT [74, 76, 77]. During the SINR calculation, a transmission power of 24 dBm and a background noise floor of -100 dBm are considered.

### 3.4.1 Results and discussion for industrial control

The communication quality and reliability of DECT systems largely depend on the DCS mechanism as this decides which channel to be used during a connection. Therefore, to evaluate the performance of DECT in an industrial control network, we mainly have to evaluate the resource allocation method (i.e. DCS) of DECT. In our simulation, we evaluate the effect of node (traffic) density by varying the number of I/O devices from low (30 I/O devices with 10 RFPs) to high (120 I/O devices, which is maximum allowable nodes with 10 RFPs) in the network. Note that all the I/O devices are always active (i.e., running with 100% duty cycling). As a performance checker, we analyze the communication latency, the number of handover, interfered connections, lost connections, SINR of the channels (used for connections), and average traffic per RFP in the network, which are explained below. Finally, we examine the effect of channel variation in Section 3.4.1.8 by changing the time varying shadowing effects and also compare the results with office environment.

#### 3.4.1.1 Latency

As mentioned earlier, DECT has a frame of 10 ms with TDD structure, when a slot is assigned on downlink for a connection after 5 ms another slot is allocated in uplink in the same time frame. In our network if a connection is established and continued, a 10 ms communication latency is guaranteed. According to our simulation results in normal industrial environment, 10 ms latency can be guaranteed precisely (with maximum 0.1% outage) for low-medium density networks (30-60 I/O devices with 10 RFPs) and with 1.49-7.63% outage for high density networks (30-60 I/O devices with 10 RFPs).\(^{11}\) Communication latency analysis is more interesting in dense network environment, where the network is traffic modeled as a Poisson distribution; such an analysis can be found in our previous work [33].

---

\(^{11}\) Outage probability can be defined here as the probability of the I/O devices that cannot achieve certain communication latency.
3.4.1.2 Connection handover

The DCS mechanism of DECT elegantly handle the connection supervision by changing the allocated channel during a connection if necessary. A handover process may initiate due to two reasons. Firstly, if a I/O device finds another RFP with significantly higher RSSI and secondly, if the SINR of the presently used channel falls below the threshold of acceptable communication. During handover, a I/O device tries to select another suitable channel without releasing the old connection. A successful handover will only take place if the new selected channel fulfills all the quality requirements. The amount of handover attempts and successful handover in low I/O density are significantly low, while in high density case a huge amount of handover have been initiated and took place. In Table 3.1, the number of successful handover attempts has been compared for different I/O densities.

3.4.1.3 Interfered connections

When an ongoing connection experiences bad channel quality and the handover attempt (to find another suitable channel) is also failed, the connection is interfered and eventually dropped. Ideally, this should not happen as the DCS takes care of it before the channel become too bad to maintain a connection. In our simulation, we get almost same number of interfered connections for every I/O density case (Table 3.1). However, this number cannot represent any clear impression about the robustness of DECT in various cases. Along with the parameter lost connections (which is discussed in next sub-section), interfered connections can clarify the capabilities of DECT in different I/O densities.

3.4.1.4 Lost connections

During connection set-up, if a I/O device fails to select a suitable channel after trying all of its allowed repeated connection attempts, the connection is considered as a lost connection. There are several reasons for this, which are as following, (i) more than one connection requests on the same channel due to the back dated channel lists; (ii) poor channel SINR and (iii) I/O devices are in out of range of the RFPs. From Table 3.1, it is clear that when the I/O density is low (30-60 I/O devices), no connections are lost. For the high I/O density (90-120 I/O devices), the number of lost connections is significantly high. In this case, the number of handover initiation is also high. This means more channels are actually used by the I/O devices as a I/O device need to maintain two connections simultaneously during handover. As the I/O devices place the connections one after another, the actual number of free channels becomes smaller and smaller. Thus, the I/O devices which try to initiate their connections in
the later phase, are unable to find free channels, and eventually those connections are lost.

3.4.1.5 Channel quality

The communication quality of any system can be quantified by the SINR of the channels used for communication. In DECT, a particular I/O device receives interference on a channel when the same channel has been used by other RFP-I/O device pairs in range. The SINR of a communication channel (which is used by a I/O device-RFP pair) may have different values in different frames during the connection period, as the other RFP-I/O device pairs may or may not use the channel in question in every frames during that connection period. In our simulation, we checked the SINR of every channels used for communication in every frames during the connection period because a handover may take place if the SINR falls below the threshold. The complementary distribution function of the channel SINR in Figure 3.9 shows that more than 60% used channels are capable to maintain the minimum required SINR (21dB) in all set-up. The channels, whose SINRs are below 21 dB, actually trigger the handover. Unsuccessful handover attempts result in interfered connection.

![Figure 3.9: Channel quality comparison in different I/O densities.](image)
3.4.1.6  Average traffic per RFP

In Figure 3.10, the average load per RFP is shown for all the different I/O density cases. The average load per RFP is calculated by counting all the used channels for communication by all the RFPs in a particular frame and taking the average among all the RFPs. In case of relatively low density (30-60 I/O devices) network, the average load per RFP is almost same as the maximum possible traffic, which is far below to the maximum allowed traffic per RFP.\textsuperscript{12} So, there are still enough rooms for new traffic in the network. In high density case, the average load per RFP is close to the maximum load capacity. In all the cases, the average traffic per base is increasing linearly with the frame number up to certain level because the I/O devices place the connections one after another and it becomes constant when all the I/O devices finished placing/ attempting for a connection. It is clear from the Figure 3.10 that in case of the low I/O density, the connections are in progress without any interruption (in most of the cases). However, in case of high density networks, some connections are interfered and lost. As a result, the average traffic in this case is slightly below the number of I/O devices per base (9 for 90 I/O devices and 12 for 120 I/O devices in the network with 10 RFPs). As, during handover process two channels are used for a connection, the average traffic per base is slightly higher than the actual number of

\textsuperscript{12} The maximum allowed traffic is 12 for a single RFP DECT system.
I/O devices on active connections.

The maximum traffic density considered in most DECT simulations for voice communication is about 5 Erlangs, which is also the suggested maximum traffic to design a network [78]. This can be considered as supporting 5 I/O devices continuously (with 100% duty cycling) per base station. From our simulation, it is clear that the communication quality cannot be guaranteed in over crowded (with traffic more than 6 Erlangs) networks. However, we simulated the networks with traffics beyond the suggested limit to check the capacity of the networks.

### 3.4.1.7 The overall performance comparison with different I/O density

While different performance matrices have been discussed in Sections 3.4.1.2 to 3.4.1.6, Table 3.1 aggregates all the simulation results, which helps to compare the overall performance of different set-ups. From the _lost and interfered connections_ column, it can be commented that the low I/O density networks can maintain excellent communication reliability, while significant disturbances are observed in high density networks. The number of handover requests increases with the I/O density as the number of placed connections increases. This also increases the probability of collision. The only exception case is the 120 I/O devices in the network. In this case, the number of successful handover is lower than that in the network with 90 I/O devices. There are two reasons for this; firstly, many handover did not succeed, which result in huge lost connections; secondly, as many I/O devices lost their connections the number of active I/O devices in the network becomes low as we did not attempt to re-establish the lost connections, which initiates relatively lower number of handover in the later phase.

<table>
<thead>
<tr>
<th>I/O density</th>
<th>Placed connections</th>
<th>Lost connections</th>
<th>Interfered connections</th>
<th>Lost and interfered connections</th>
<th>Handover</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>60</td>
<td>3000</td>
<td>0</td>
<td>13</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>90</td>
<td>4500</td>
<td>64</td>
<td>3</td>
<td>67</td>
<td>29580</td>
</tr>
<tr>
<td>120</td>
<td>6000</td>
<td>456</td>
<td>0</td>
<td>456</td>
<td>13121</td>
</tr>
</tbody>
</table>
3.4.1.8 Effect of variation in channel model

So far, we have evaluated the performance of DECT networks in a normal industrial environment where the channel parameters varies relatively slowly over time. As from the discussions above, we find that the network can only guarantee good communication quality for low to medium I/O density cases, we will now examine the effect of channel variation only for those networks. We also observe the performance of the networks in office environment. To generate the channel in office environment, we removed the time varying shadowing from the propagation model. However, a uniformly distributed random shadowing is considered as proposed in ETSI model. The amount of this shadowing is considered as a constant for a RFP-I/O device pair during the whole connection period. \(30 \text{ ind ch 1}\) represents the networks with 30 I/O devices, where a time varying industrial channel model with standard deviation 1 dB/10 ms (according to in Equation 3.2) is used. Along with this normal industrial environment, we also considered two other industrial channels with fast shadow fading, where \(30 \text{ ind ch 2}\) represents a channel model with standard deviation of 2 dB/10 ms and \(30 \text{ ind ch 3}\) represents a channel model with standard deviation of 3 dB/10 ms in Equation 3.2. From the \textit{Lost and interfered connections} column of Table 3.2, we see that DECT works perfectly in the office environment (for which it was actually built) with no connection loss. It can still maintain satisfactory performance in normal industrial environments for both 30 I/O devices and 60 I/O devices in the network. The performance of the networks become poor if large variance in shadowing \((3 \text{ dB/10 ms})^2\) has been applied. The number of handover attempts also increases significantly in those cases. Many I/O devices could not find single base station for a while in the high variance case, which is also a reason of the poor performance and huge amount of handover attempts.

<table>
<thead>
<tr>
<th>I/O density</th>
<th>Placed connections</th>
<th>Lost connections</th>
<th>Interfered connections</th>
<th>Lost and interfered connections</th>
<th>Handover</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 off envt</td>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>30 ind ch 1</td>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>30 ind ch 2</td>
<td>1500</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>936</td>
</tr>
<tr>
<td>30 ind ch 3</td>
<td>1500</td>
<td>0</td>
<td>78</td>
<td>78</td>
<td>19300</td>
</tr>
<tr>
<td>60 off envt</td>
<td>3000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>60 ind ch 1</td>
<td>3000</td>
<td>0</td>
<td>13</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>60 ind ch 2</td>
<td>3000</td>
<td>121</td>
<td>21</td>
<td>142</td>
<td>1797</td>
</tr>
<tr>
<td>60 ind ch 3</td>
<td>3000</td>
<td>320</td>
<td>257</td>
<td>577</td>
<td>28541</td>
</tr>
</tbody>
</table>
In Figure 3.11, we show the quality of the channel (in terms of cdf of channel SINR) which are used for the connections. The quality of the channels is found to degrade with the increase in shadow fading variance. However, this figure does not give us the complete picture because in calculation of cdf, the SINRs of some channels are omitted, which are mentioned below. In high I/O device density cases, some of the I/O devices fail to select a suitable channel for the connection which are considered as lost connections. The SINR calculation is not possible as no actual channels have been allocated for those connections. Again in case of large variance in shadowing effect, some of the connections are lost due to the channel unavailability. In this case, no RSSI readings are available on the I/O devices to calculate their SINRs. Thus, the cdf only represent the quality of the channels which are actually allocated for connections. From Table 3.2, we also observe that the number of interfered connections is directly related to the number of handover requests.

![Graph](image)

**Figure 3.11:** Comparison of channel quality in office and industrial environments.

In case of office environment, we found that 10 ms latency can be guaranteed with 100% reliability, while in industrial environments, we still can guarantee this for low-medium density networks with low outage probability (0-4.7%). Only in extremely harsh industrial environment, we get high outage probability (5.2-19.23%), however this type of fast time varying channel environment are rare.
Table 3.3: Performance evaluation of multiple DECT-transceivers based control systems.

<table>
<thead>
<tr>
<th>I/O density</th>
<th>Placed connections</th>
<th>Connection loss (one DECT transceiver)</th>
<th>Connection loss (two DECT transceivers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 ind ch 1</td>
<td>$2 \times 3000$</td>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td>30 ind ch 2</td>
<td>$2 \times 3000$</td>
<td>285</td>
<td>0</td>
</tr>
<tr>
<td>30 ind ch 3</td>
<td>$2 \times 3000$</td>
<td>1172</td>
<td>14</td>
</tr>
</tbody>
</table>

3.4.2 Improved reliability with multiple DECT-transceivers based system

As discussed in Section 3.4.1.7 and Section 3.4.1.8, the channel conditions of an industrial environment can significantly affect the communication reliability and latency. It is not always possible to avoid packet losses in an industrial environment even by utilizing dynamic channel allocation schemes (e.g., DCS scheme of DECT) to choose a better channel for communication. Although it might not be an issue in many industrial systems if few packets containing sensor data are lost, it can create a system failure if the packets containing control decision are lost or get delayed. To have a fail-safe industrial control system, spatial diversity techniques can be used. We use a simple mechanism to achieve spatial diversity from the I/O devices’ point of view where two DECT transceivers are attached on each I/O device. A total 100 networks have been simulated to evaluate the performance of multiple DECT-transceivers based control networks. It has been observed that a significant number of connections are interfered when each I/O device has one DECT transceiver for the communication with RFPs. In case of such connection failures, the I/O devices have to re-establish the connection with the base stations which takes some time. The corresponding I/O devices can not transmit their data or be actuated during this down period, which might not be acceptable in many industrial control applications. On the other hand, an I/O device having two DECT transceivers use different (independent) channels to transmit two copies of its packets by utilizing dynamic channel selection scheme, which increases the probability of receiving one copy of these messages correctly by the RFPs. Thus, such I/O devices can still continue to communicate with the base stations when one of its transceiver loses its connectivity. Table 3.3 shows that all of the I/O devices with two DECT transceivers can maintain their connections with the base stations continuously except the case of highly dynamic industrial environment where less than 0.5% connections have been interrupted. Similar concept of spatial diversity scheme is used in one of our
proposed schemes in Section 5.3.2 where the I/O devices transmit two copies of
the same packet to two different routers to improve communication reliability. Al-
though, such schemes can guarantee excellent communication reliability for indus-
trial control systems, it reduces the system throughput and doubles the I/O energy
consumption.

3.5 Concluding remarks

Advances in IWSNs demand the developments of new technologies for industrial
automation with increased capacity and reliability. This creates new challenges for
the researchers to efficiently design the technologies. In this chapter, we evaluate the
performance of DECT in some of these envisioned industrial setups by analyzing the
communication reliability of DECT. Although, DECT was primarily developed for
indoor cordless communications, the DCS mechanism of DECT also made it suitable
to combat industrial harsh environment. Dynamic channel selection is the heart of
the DECT system which enables the I/O devices to re-use the radio resources in a
flexible and distributed way, which makes the network far more scalable than WirelessHART/ISA100.11a networks that utilize blind channel hopping techniques. We
found that DECT can beautifully handle dense IWSN by providing excellent com-
unication with low latency. Only a few connection attempts have been denied to
grant a channel on first attempt in our simulation, which have been taken care of by
placing the connection on some other suitable channel in next frames. The ability
to choose best parents (RFPs) from the I/O devices perspective can better address
the local interference issues. Such a scheme is adapted in our proposal in Chapter 4.
Nevertheless, DECT/DECT-ULE is able to support many requirements of IWSN ap-
lications, it is still not energy efficient to be adopted for many industrial monitoring
application. So, there are still rooms for improvement to make DECT more suitable
for IWSNs. In addition, the high installation cost of fixed infrastructures required for
DECT-IWSN makes it unattractive for many industrial applications.
While capable of providing reliable communication in industrial harsh environments, widely used industrial systems such as WirelessHART and ISA100.11a, cannot cope with network disturbances in a real-time manner due to their centralized network architecture. Fixing broken links in dynamic situations often requires a lot of message exchanges in a centralized system, which triggers unpleasant delays. In addition, such systems can not support resource constraint I/O devices. Hierarchical network architectures, on the other hand, are capable of addressing most of these issues with low latency and overhead. Such network architecture divides industrial networks into two parts, namely the service network and the local network. The service network is responsible for forwarding data from the source to the destination while the local network is responsible for collecting I/O data and send it to the cluster head, and vice versa. In this chapter, we discuss the details of the service network for industrial applications, i.e., the network formation, joining and data communication.

Partially based on:


4.1 Introduction

The radio channel quality varies considerably in an industrial environment. Coping with such dynamic situations often requires a lot of message exchanges in a centrally managed network, which incurs high latency [9, 51, 79]. Thus, industrial networks utilizing centralized management approach such as WirelessHART and ISA100.11a, cannot cope with network disturbances in a real-time manner. I/O devices in these networks, have to go through a complex and energy consuming network joining process before being able to publish data. Additionally, the resource constraint I/O devices might temporarily lose their power that disconnects them from the network. In response, the I/O devices have to rejoin the network to resume their tasks. However, such I/O devices often do not have the capabilities to handle the network joining overheads of a centrally managed network. These problems are further exacerbated as the network scales up where the I/O devices are several hops away from the SM. Proper enhancements of the existing standards are thus essential to provide real-time communication in dynamic scenarios as well as to make these systems suitable for energy constrained I/O devices.

To address the above mentioned issues, we propose an extension to the ISA100.11a standard named ISA100.11a* that utilizes a hierarchical network management scheme. In ISA100.11a*, a central SM delegates some management responsibilities and block of communication resources to the routers. Then, the routers can schedule communications with I/O devices in their local star sub-network. The communication schedules and graphs between the routers in the mesh network are constructed by the SM, the same way as in ISA100.11a. Although hierarchical centralized schemes can address the requirements of the harvester powered I/O devices in industrial networks, a centralized system still faces the scalability issue. For improved scalability, resource reuse (e.g., cells) is essential at different parts of the networks. Motivated by this, we propose a hierarchical distributed management scheme named D-MHR for industrial applications that can reuse the communication resources in non-interfering areas. As a result, the proposed hierarchical scheme achieves improved network scalability along with providing real-time communications for industrial applications.

I/O devices in both of the proposed schemes can dynamically select the best parents (routers) based on their local statistics and the global rank of the routers. This is particularly interesting for resource constraint I/O devices to cope with network disturbances and while rejoining the network in case of edge failures. One can argue about the ISA100.11a’s policy to store the allocated resources in I/O memory and use this when it wants to rejoin the network after losing the network connectiv-
4.2 Overview of ISA100.11a

However, in large-scale dynamic networks, the channel condition might change frequently, and using the old resources to communicate with the assigned routers might not be useful any more. In this chapter, we will evaluate the consequence of such an approach. The I/O device’s capability to choose/change the associated routers in the proposed ISA100.11a* and D-MHR schemes can better cope with time varying channel condition of an industrial environment as well as makes the industrial networks suitable for resource constraint I/O devices. Table 4.1 compares the ISA100.11a, ISA100.11a* and D-MHR in different aspects.

Table 4.1: Functional and operational comparison between different approaches.

<table>
<thead>
<tr>
<th>Item</th>
<th>ISA100.11a</th>
<th>ISA100.11a*</th>
<th>D-MHR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Management</td>
<td>Centralized</td>
<td>Hierarchical</td>
<td>Hierarchical distributed</td>
</tr>
<tr>
<td>Routing</td>
<td>Graph Routing</td>
<td>Graph Routing</td>
<td>RPL (Ranking on OFs)</td>
</tr>
<tr>
<td>Scheduling</td>
<td>Centralized (Scheduled by SM)</td>
<td>Hierarchical</td>
<td>Distributed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Centralized (Scheduled by SM)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Does not support</td>
<td>Delegating the</td>
<td>The communication</td>
</tr>
<tr>
<td></td>
<td></td>
<td>authority is</td>
<td>resources are allocated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>managed by SM</td>
<td>by the routers in a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>distributed manner</td>
</tr>
<tr>
<td>Resource delegation to routers</td>
<td>Does not</td>
<td>Calculated by SM</td>
<td>Calculated by RPL</td>
</tr>
<tr>
<td></td>
<td>Support</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rank calculation</td>
<td>Does not</td>
<td>Calculated by SM</td>
<td></td>
</tr>
<tr>
<td>Neighbor selection for I/O devices</td>
<td>Support</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Selected by SM</td>
<td>Selected by I/O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>based on network reports</td>
<td>devices</td>
<td>devices</td>
</tr>
</tbody>
</table>

To evaluate the performance of the proposed schemes in comparison with traditional IWSNs, we use ISA100.11a as a baseline for its versatile applications. Thus, before going into the details of our proposed schemes, we discuss the centralized management approach and the services used by ISA100.11a in Section 4.2. Then in Section 4.3, we elaborate the proposed ISA100.11a* and Section 4.4 explains D-MHR. After this, we evaluate the proposed schemes in Section 4.5 in terms of communication reliability and latency. Finally, we conclude this chapter in Section 4.6.

4.2 Overview of ISA100.11a

ISA100.11a is developed on top of IEEE 802.15.4-2006 Physical layer by specifying new Data-link, Network, Transport and Application layers to provide robust communications for industrial automation on 2.4 GHz ISM band. An ISA100.11a net-
work has two parts: the plant network and the wireless network as shown in Figure 4.1. The wireless network consists of two types of nodes namely routers and I/O devices. Routers collect data from the I/O devices and forward this towards destination through other routers by forming mesh networks. On the other hand, I/O devices only transmit and receive data to and from the routers, and do not participate in the routing task. The routers periodically broadcast some reference messages known as advertisements, containing system information to facilitate I/O joining.

![Figure 4.1: ISA100.11a sample network.](image)

### 4.2.1 Operating principle of ISA100.11a

#### 4.2.1.1 Channel hopping

A central SM handles all the communications in ISA100.11a by utilizing time division multiple access (TDMA) on top of channel hopping mechanism. Based on the requirements of I/O devices, SM decides which paths in the mesh network would be used and reserves communication resources along the paths by making schedules. For this, SM considers collection of time slots (e.g., 25 slots) known as superframe. Several links are established to forward the I/O devices’ data towards the destination, where link is a connection between a pair of nodes (e.g., I/O device-router, router-router). A link is scheduled in a particular timeslot and repeated based on the
publication period of the node; however, it switches the physical channel in every
instance to achieve higher reliability. The sequence of physical channels followed by
the links is known as hopping pattern. Multiple links can be scheduled in the same
timeslot by using different channel offsets, where channel offset is a virtual number
which can be considered as a delay on top of hopping pattern. The relationship
between hopping pattern and physical channels can be expressed with following
formulas,

\[
\text{index} = (\text{ASN} + \text{Ch}_{\text{off}}) \% \text{N}_{\text{Ch}},
\]

\[
\text{Ch}\# = \text{Channel Hopping Sequence (index),}
\]

where, ASN is the start slot number, Ch\_off is the channel offset, N\_Ch is the number of
available channels and Ch\# is the physical channel number.

An intuitive example is given here to explain the relationship between hopping
pattern, channel offsets and the physical channels. Let us consider the following
hopping pattern,

\[\text{hop}_1 = 19, 12, 20, 24, 16, 23, 18, 25, 14, 21, 11, 15, 22, 17, 13, 26;\]

where, the numbers represent the corresponding physical channels in IEEE802.15.4
standard. Router 1 is following hop1 with channel offset 0, it uses physical channel
19 in slot 1, physical channel 21 in slot 10 and so on. Assume, Router 1 uses slot 2 for
advertisement broadcast in every superframe. If it uses channel 12 in superframe \(N\),
following the hopping pattern mentioned in Equation 4.3, it will use channel 23 in
superframe \(N + 1\), as shown in Figure 4.2. Again, if we consider Router 2 is following

Figure 4.2: Relationship between physical channels and channel offsets in an
ISA100.11a superframe.
hop\_1 with channel offset 7. The sequence of channels will be 25, 14, 21, 11, 15, 22, 17, 13, 26, 19, 12, 20, 24, 16, 23, 18. Now, if Router 2 uses slot 5 for its advertisement broadcast in every frame, it will use channel 15 and 26 in superframe $N$ and $N + 1$ respectively.

### 4.2.1.2 Advertisement broadcast

The routers in ISA100.11a can broadcast their advertisements either on any of the IEEE802.15.4 channels or limit those on subset of channels.\(^1\) The SM schedules broadcasting cells (channel offset and slot combination) for the routers to facilitate advertisement broadcasts. ISA100.11a standard also mention active joining approach for reduced capacity nodes, where the routers occasionally listens for potential solicitations from I/O devices by using slow hopping pattern. Upon receiving a solicitation the router broadcasts an advertisement on the next slot. Such scheme helps the I/O devices with imprecise synchronization (i.e., without knowing the exact slot boarders) to join the network quickly. Note that I/O devices still need to have superframe synchronization to use active joining approach.

### 4.2.1.3 I/O joining

When an I/O device wants to join the network, it has to discover at least one router by scanning all the available physical channels to receive advertisements from the routers. An I/O device scans each channel for a limited duration and then moves to the next channel. After detecting advertisements during the scanning phase, the I/O device sends a join request to the proxy router, which is then forwarded to the SM through the mesh network. The I/O device has to keep listening on the joining links that is mentioned in the advertisement, for join response. This listening duration depends on the hop distance between the I/O device and the SM. The SM then writes the management keys, adds links and frames for the data communication. Upon acknowledging these management messages, the I/O device becomes ready to publish actual data. The complete I/O joining procedure is depicted in Figure 4.3.

### 4.2.1.4 I/O data publication

Upon joining the network successfully, an I/O device receives resources (links) from the SM according to its requirement. For reliability, every node in ISA100.11a network keeps a list of two best neighbors suggested by the SM in both up-link and down-link directions. However, one of these links is selected randomly in every instance.

\(^1\) The details are beyond the scope of this chapter. However, such a scheme is used in our proposed network joining scheme for resource constraint I/O devices in Chapter 5.
4.2 Overview of ISA100.11a

Figure 4.3: I/O device joining procedure in ISA100.11a.

for actual data publication. In case of packet loss (can be identified through unacknowledged transmissions), the I/O device re-transmits the packet by using either a dedicated slot scheduled in later superframe or a shared slot (which allows communications from multiple nodes, thus collision may occur).

4.2.2 Evaluation of the channel hopping mechanism used in ISA100.11a

To evaluate the performance of ISA100.11a’s channel hopping mechanism in an industrial environment we have conducted a field trial in Turin in early 2014 with the VMON-ISA100.11a wireless sensor nodes developed during WiBRATE project. The experiments shows that end-to-end path reliability and data reliability of the deployed network are very good (almost 100%), even though up to 9% packet loss were seen. This is achieved with packet re-transmissions and channel hopping techniques employed in ISA100.11a. Additional experiments also shows that the channel hopping mechanism of ISA100.11a can achieve excellent end-to-end reliability by overcoming the industrial channel fading.

Later in December 2014, another testing campaign have been conducted with more sensor nodes (five V-Mon ISA100 nodes and four Nivis VS210 development boards) over a period of 1 week. Here the nodes are spread out in a slightly larger area. The experiment setup is illustrated in Figure 4.4 (right). A typical network
The topology obtained during the experiments is shown in Figure 4.4 (right). It shows that the ISA100 nodes form a multi-hop network where some nodes go up to 3 hops far apart from the SM. Note that the network topology changed dynamically during the experiment to cope up with channel variation.

During the experiment, WiFi has been operating on the three mostly used channels (IEEE802.11 channel 1, 6, 11) continuously. In addition IEEE802.11 Channel 2 has also been operating occasionally. The end-to-end path reliability and data reliability of the deployed network are very good when the hopping pattern (all channels) as mentioned in Equation 4.4 has been used.

\[ h_{p1} = 19, 12, 20, 24, 16, 23, 18, 25, 14, 21, 11, 15, 22, 17, 13. \]  \hspace{1cm} (4.4)

To analyze the impact of channel hopping, we limit the number of channels in the
Figure 4.5: Mean packet loss probabilities of the nodes with standard deviation range during the ISA100.11a field trial. The top figure groups the nodes having regular patterns and the bottom figure groups the nodes having irregular patterns.
hopping pattern to three and later to one during the experiment. To select interesting combination of channels, we first choose

\[ \text{hp}_2 = 15, 20, 25, \]

for one experiment with a hope that it would achieve the best packet reception rate as these channels are non-overlapping with commonly used IEEE802.11 channels. For the next experiment, we choose

\[ \text{hp}_3 = 12, 17, 22. \]

This pattern should provide bad results as it would have interference from WiFi when commonly used IEEE802.11 channels are used in the neighborhood. We also conduct two other experiments by turning off channel hopping completely, i.e., by using a fixed channel for communication. The hopping patterns considered in these experiments are

\[ \text{hp}_4 = 25, \]

and

\[ \text{hp}_5 = 12. \]

Figure 4.5 illustrates the mean packet loss probabilities of the sensor nodes participating in the network shown in Figure 4.4 (left) with the five different hopping patterns mentioned above. It is clear that most of the sensor nodes achieve the best performance when \( \text{hp}_1 \) is used. Then, the packet loss probabilities increase gradually with the use of hopping patterns \( \text{hp}_2 \) to \( \text{hp}_5 \) for most of the nodes as can be seen in Figure 4.5 (top). This behavior is expected as the hopping patterns \( \text{hp}_2 \) to \( \text{hp}_5 \) has lower number of channels than that of the hopping pattern \( \text{hp}_1 \). The nodes having line of sight with gateway such as node 013B, 3838, perform better than the nodes are in non line of sight with gateway such as node 3837 and 3839, due to their geometrical location and metal blockage in the path. However, the node 3836, 2677, 2730, 383A give irregular patterns as shown in Figure 4.5 (below). There are several reasons behind this. First of all, the experiment has been conducted in an uncontrolled environment where WiFi was randomly used by people which may affect particular nodes. Secondly, some of these nodes are physically located very close to the gateway (often within one hop distance). As a result, these nodes are able to achieve higher packet reception rates with few re-transmissions. However, the effect of packet losses aggregates for the nodes several hops away from the gateway, which in turn gives bad packet reception rates. Thirdly, during the experiment, the movement of the machinery attenuates the signal in some cases that creates some ir-
regularity in the packet reception rate which is not correlated with interference from WiFi. Regardless of the varying packet loss statistics achieved during this experiment, we can conclude that the channel hopping scheme of ISA100.11a can provide reliable communication in an industrial environment.

4.3 ISA100.11a*: The ISA100.11a extension to resource constraint I/O devices

ISA100.11a has several limitations to address the requirements of modern industrial applications, such as supporting resource constrained I/O devices, large-scale networks, response in dynamic situations, etc. Thus a service network capable of speeding up the I/O (re-)joining as well as fixing broken links with minimal management overhead is essential.

The hierarchical management scheme of proposed ISA100.11a* delegates the authority over parts of the communication resources to the routers to handle I/O requirements in their local star sub-network. Based on I/O density and their local statistics, the routers ask for appropriate resources from the SM. After getting resources from the SM, routers allocate these among potential I/O devices upon receiving their join requests. The remaining network resources are managed by the central SM, which constructs the routing graphs and communication schedules between the routers in the service network. A sample network topology in ISA100.11a* with routers having management capabilities and the corresponding superframe structure are shown in Figure 4.6, where the SM manages the first block of resources and and the remaining resources are allocated to different routers for their own local management. The size of the blocks allocated to routers is set based on expected network load, which can vary according to the number of I/O devices associated with each router and their traffic characteristics.

The routers use their own resources to send both the join reply and the contract reply in response to I/O devices’ requests, unlike the traditional ISA100.11a network where this is handled by the SM. Several Tx and Rx links are defined by the routers on which the I/O devices can send the contract requests including its traffic characteristics. The routers use their local resources to define links for potential I/O data which speeds up the I/O joining procedure. Harvester powered I/O devices might frequently shut down and lose their connectivity with the routers. However, the router should not release the communication resources reserved for these I/O devices when no updates about their presence are received for a while. Since the I/O devices are not participating in routing tasks, it is not necessary to remove the resources reserved for them very fast from the network. This policy lets the harvester
powered I/O device work more efficiently in the network.

The I/O devices in ISA100.11a* are able to choose/change the associated routers based on their requirements (e.g., end-to-end latency, reliability, power budget). An

![Diagram of ISA100.11a* network topology and superframe structure.](image)

I/O device keeps the statistics of the overheard neighbor routers in a Candidate Router table in which it updates the status of its connectivity with the routers. To let the I/O devices choose the best router(s), the routers advertise their ranks which
4.3 ISA100.11a*: The ISA100.11a extension to resource constraint I/O devices

are basically qualifying numbers defining the router’s relative position/grade with respect to the gateway based on different objective functions (OFs). The functional description of the network devices (routers, I/O devices, SM) in ISA100.11a* are explained below.

4.3.1 Management phases in routers

The routers in ISA100.11a* are considered to have some management capabilities to manage small star sub-networks without increasing the complexity. The following additional management phases need be added along with the existing ISA100.11a standard to let the routers manage the I/O devices in their sub-networks.

Contract or end-to-end connection establishment: The routers with management capabilities send contract requests to the SM to reserve communication resources for the multipath route towards the gateway in the uplink and downlink direction as well as for their potential children in the local star-network.

Resource delegation to routers: The authority over parts of the communication resources will be delegated to routers to manage their one-hop star sub-networks. The delegation takes place after a negotiation procedure between routers and the SM. Each router is capable of running a simple network management algorithm to manage their small star sub-network as shown in Figure 4.6 by using the allocated resources (e.g., channel offset or chunk of cells). To provide real-time communication between an I/O device and its destination (i.e., the gateway or another I/O device), the routers might also reserve the communication resources (over-provision) beforehand, along the path to the destination in the mesh network.

The communication resources delegated to the routers depend either on the I/O density from the routers perspective or on a fixed per-allocation. Later, the routers might ask for more resources upon detecting more I/O devices or traffic changes. Each router updates its candidate I/O table in which the overheard I/O devices’ address and statistics (e.g., RSSI and RSQI values) are stored. A router uses this information to request resources from the SM for potential communication with the listed I/O devices. The reservation is undertaken either in the local star network or between the routers in the multipath routes toward the gateway. When an I/O device selects its parent (router), the router could use the already reserved resources to create local links with the I/O device. Each router then update the I/O neighbor table (similar to neighbor diagnostic table in ISA100.11a standard) with the address and statistics (e.g., mean RSSI, number of packets received, and number of missed ACK) of the newly associated I/O devices.
4.3.2 Management phases in I/O devices

I/O devices in ISA100.11a* do not have any idea on the network management scheme used by the SM. The phases an I/O device has to go through before able to publish its data in an ISA100.11a* network are discussed below.

Router selection and network joining: Upon start-up, an I/O device starts scanning the physical channels to receive advertisements from the neighboring routers. It updates the candidate routers table with the statistics of the overheard neighboring routers (e.g., received RSSI and rank of the router). The updating rate depends on the capabilities of the device. Each I/O device also maintain a neighbor routers diagnostic table (similar to the neighbor diagnostic table in the ISA100.11a standard) containing information about its associated routers. The routers broadcast their ranks in terms of different metrics such as reliability, latency, and power consumption to reach the gateway, in the network. An I/O device chooses the best router based on their ranks and its own local statistics. Then it sends join requests to the selected router through the advertised Rx link and listens on the advertised Tx link to receive the reply. The router processes the request locally and sends an activation command to the I/O device. Then, the router writes local resources in the communication tables (e.g., superframes, links, graphs, and channel tables) of the I/O device. The I/O device may select more than one router to improve reliability. In such cases, it sends new joining requests to the next routers.

The I/O device then starts to report per-channel and per-neighbor statistics (i.e., channel diagnostics and neighbor diagnostics reports) to the selected routers. The routers process the received reports locally unlike the traditional way of sending the report directly toward the SM. The routers inform the SM about their subordinate I/O devices. As a result, the SM and the gateway know how to reach to the I/O devices through the selected routers.

Contract or end-to-end connection establishment: An I/O device sends separate contract requests to each of the selected routers. Before publishing the sensor data, the I/O device needs to reserve the resources to communicate with the neighboring routers as well as to reach the final destination through the routers in the multi-path routes. This resource reservation ensures real-time communication between the I/O devices and their destinations. To support periodic communications, resources might be reserved in the slotted hopping period (considered in this chapter), while in case of event based traffic, slow hopping and slotted-CSMA scheme can be used (discussed later in Chapter 5).

A router sends a new contract request to the SM upon receiving the I/O contract
requests to reserve the communication resources between the routers in the mesh network. The router allocates resources based on the traffic characteristics for further communication with the I/O device and replies to the device with the contract response. The router uses its own resources, which are already delegated, to write the new links and superframes in the link table and superframes table of the I/O device. If the delegated resources are not sufficient to address the requirement of the I/O device, the contract response of an I/O device is postponed until the router receives additional resources from the SM.

The routers can setup the virtual paths to the destination by over-provisioning some resources. In such cases, the routers ask the SM to reserve more resources on the path toward the gateway in the mesh network. As a result, the times required for processing and establishing the contract for potential I/O devices can be reduced. When subsequent virtual channels have the same source and destination, they need not to be provisioned every time when a new contract request is received from a new I/O device. The router receives the final contract reply from the SM upon allocating the required resource in the mesh network. I/O devices in ISA100.11a* receive the contract responses from the routers much earlier compared to the traditional ISA100.11a approach. Upon receiving the contract response, the I/O devices start publishing data to the routers and the routers forward the traffic toward the destinations by using existing resources.

**Contract termination, deactivation and reactivation:** In an industrial environment, the link quality and the rank of the routers may vary frequently. As a result, an I/O device might decide to change its parent. To do so, an I/O device terminates its contract by sending a terminate request to the router which then release the resources from the I/O device. However, based on the over-provisioning policy, the SM might not free up reserved resources in the mesh network for potential future reuse. This is particularly interesting for energy harvested I/O devices who lose their connectivity with the network for a while. However, when a router determines that an I/O device is no longer part of the network, it terminates the contracts associated with that I/O device based on a timeout mechanism. Eventually, the network resources that were allocated for supporting those contracts are freed up.

**Data publication:** To publish data, an I/O device first sends it towards the assigned router(s), including the destination information. The router uses mesh routing and forwards the data toward the destination. If the route toward the final destination does not exist, the data will be forwarded toward the gateway. Unlike the traditional ISA100.11a where SM constructs an uplink (or downlink) graph from the
I/O device to the gateway, here the I/O device uses the uplink (or downlink) graph of the selected router which acts as a proxy router to reach the gateway.

**Interference management:** Similar to the ISA100.11a standard, the I/O devices in ISA100.11a* utilizes channel hopping on a link-by-link basis in addition to the traditional blacklisting on the whole network. Each I/O device updates the statistics on channels and neighbors including the ranks in the *channel diagnostic table* and *neighbor routers diagnostic table* respectively. Different network edges may experience different packet losses in presence of interference which might change the rank of the routers. The I/O devices in ISA100.11a* can choose the best available routers based on new local and global network statistics as described earlier. This approach can provide robust performance in a large-scale industrial network.

### 4.3.3 System Manager Extensions

The SM of ISA100.11a* handles the communication schedules between the routers in the mesh network in a centralized manner while delegating the authority over blocks of resources to the routers to locally manage their star-sub networks. The SM constructs the uplink/downlink graphs and schedules the communication in the constructed graph. It also receives the router statistics and use this information to calculate the global ranking of the routers in the mesh network based on the defined OFs. The mesh TDMA Markov chain model has been used to calculate the routers rank in our scheme [80].

### 4.4 D-MHR: An Hierarchical distributed management scheme for IWSNs

In this section, we present a hierarchical distributed management scheme named D-MHR for industrial applications requiring improved scalability as well as supporting resource constraint devices in the network. The routers in D-MHR form a mesh network while the I/O devices are part of the local star networks as shown in Figure 4.7. The superframe of D-MHR illustrated in Figure 4.7 (below), has the similar structure as in IEEE 802.15.4e-TSCH mode [49]. The routers in D-MHR divide the communication resources among themselves in a distributed manner by listening to the advertisements of their neighbors. Routers reserve resources for communication with potential I/O devices and neighboring routers. Every router includes the statistics of the resource used by itself and its neighbors in the advertisement. This helps the routers to avoid using the same resources as their neighbors in two-hop radius.
The communication resources in D-MHR are defined as a group of consecutive slots in the superframe, referred to as segment. A particular router can reserve multiple segments. With smaller segment, the resource reservation becomes more dynamic and flexible. However, it increases the network management overhead to keep track and update this distributed resource reservation. For practical implementation, we consider a complete row in the data communication period of the TSCH superframe (i.e., a channel offset) as a segment.

After getting synchronized with the network, the I/O devices in D-MHR select the best two routers to provide reliable paths. The I/O devices use the network statistics received through the advertisements (e.g., RSSI of the neighboring routers, rank of the routers) to choose the best possible routers according to their requirements. The I/O devices use the segments reserved by the routers for further communications. An I/O device informs the selected routers about its traffic character-
istics to reserve resources accordingly. The D-SAR signaling protocol is applied for the resource reservation purpose [79].

In a multi-channel system utilizing channel hopping, node joining and neighbor discovery become challenging. To address these issues, we divide the D-MHR superframe into two periods namely the \textit{advertisement broadcast period} and the \textit{data communication period} as shown in Figure 4.7 (right). During the advertisement broadcast period, nodes either broadcast their control messages (e.g., advertisements, routing layer messages) or listen to their neighbor’s control messages. As no further communications are scheduled in this period, effective data sharing between the nodes is guaranteed. To facilitate faster neighbor discovery, we limit the number of channels used in that period to \textit{three} channels$^2$. During the data communication period, the routers choose particular channel offsets to provide unicast communications. The network devices may in turn use the broadcasting and data communication periods to create a superframe of any length that is an even multiple of a basic superframe length, in which these periods are repeated.

The functional description of the network devices (routers with management capabilities, I/O devices) in D-MHR are explained below.

\subsection*{4.4.1 Management phases in routers}

Routers in D-MHR, are considered to have capabilities to manage I/O devices in a sub-network. The routers handle I/O joining and distribute communication resources to them. The management phases, a router go through in D-MHR, are discussed below.

\textbf{Network joining and neighbor discovery:} In this phase, a new router scans the available physical channels to receive advertisements from the neighboring routers. Upon receiving advertisements from several routers, a new router selects the best neighbors and sends the join requests to them. The advertiser then transmits a join response to the new router.

\textbf{Resource selection for advertisement broadcast and data communication:} Upon joining the network, the new router can start broadcasting its advertisement. For this, the new router has to choose a free advertisement cell and a free channel offset in the superframe. D-MHR includes the advertisement cell number and channel offset number of an router and its neighbors in the advertisement of each router. Thus

\footnote{In our implementation, the non-overlapping IEEE802.15.4 channels with commonly used IEEE 802.11 channels are selected for this purpose. However, different combinations can be implemented based on the application environment and regulatory issues.}
by receiving advertisement from neighboring routers, a new router can effectively
gather information about its two-hop neighborhood.\textsuperscript{3} This enables the routers to
choose a free advertisement cell as well as a channel offset in a distributed manner.

**Initial communication with neighbors:** The neighbor connection manager mod-
ule of each router in D-MHR, uses a handshaking mechanism to define one Tx and
one Rx link with each of its neighboring routers [79]. These links enable a router to
communicate with all of its neighbors.

**Route construction:** D-MHR uses RPL in the routing layer to find a path towards
the gateway. By generating RPL control messages, the routing entries in the inter-
mediate nodes as well as a complete path toward the new router will be constructed.
Several control messages are periodically forwarded through the network to con-
struct the *up* (multipoint-to-point) and *down* (point-to-multipoint) routes. To select
the best routers as parents, routers in D-MHR use the statistics of *neighbor router table*
and the *rank* of neighbor routers.

**Multipath Routing in RPL:** For improved reliability, it is desirable to use a multi-
path route between a source and its destination. After receiving I/O data or man-
agement messages from a child, each router chooses the next hop randomly from
the two best parents in the *up* direction to enables reliable multipath routing in RPL.
The destination node (router or I/O device) forwards *destination advertisement object* (*DAO*) messages to its two best parents and finally to the gateway in the *down* di-
rection. By this way the intermediate routers store the potential multipath routes in
their routing table for the *down* direction.

**Contract or end-to-end connection establishment:** In D-MHR, a distributed sig-
nalizing protocol named D-SAR has been utilized by the source node to send the setup
message toward the destination node along the defined route [79]. The setup mes-
gage includes parameters such as a list of suggested common unused timeslots for
further communication with the next hop, a final destination address, traffic ID, and
a requested publishing period. The receiver of the setup message then checks its
available communication resources. When available, the receiver chooses one times-
lot from the suggested free timeslots based on the publishing period of the source
and allocates this by writing a new link in the related tables of the data link layer.
The intermediate receivers then continue to forward the setup message until the des-
tination node receives it. The destination node can either accept or decline the new

\textsuperscript{3} We assume that the two-hop information guarantees that two routers which are in interference range,
do not transmit at the same time, and hence do not cause collisions.
connection request from the source node by sending a connect message or release complete message.

**Coping with internal interference in the network:** The routers can reuse a channel offset beyond its two hop neighborhood. In realistic scenarios, the interference range of a node can be much larger than its transmission range. When two pairs select the same channel offset during concurrent communications, interference will be unavoidable. Thanks to the scheduled communication concepts, this internal interference can be detected by observing the packet loss statistics of those cells after reservation. The router that detects the potential conflict can change its chosen channel offset.

### 4.4.2 Management phases in I/O devices

The steps an I/O device has to go through before able to publish its data in D-MHR are discussed below.

**Joining and neighbor discovery:** I/O devices scan the physical channels to receive advertisements from the neighboring routers. Upon receiving advertisements, an I/O device updates its *candidate router table* with some information (e.g., received RSSI, RSQI, and channel offset of the router). In addition, each I/O device stores the statistics about linked routers in a related table. These local statistics and the rank of the router help an I/O devices to select two best routers for further communication. Then, the I/O device sends join requests to this selected router(s) through the advertised Rx link. Upon receiving a join request from an I/O device, the router processes the join request locally and sends an activation command to that I/O device.

**Selection of an advertisement cell:** After receiving the activation command, a new I/O device starts to send advertisements. The selection procedure of a free advertisement cell is similar to that of a router. However, I/O devices do not need to select channel offsets for data communications, instead, they follow the selected router’s channel offset.

**Initial communication establishment:** The initial communication establishment phase of the I/O devices is similar to that of the routers.

**Router Selection and Route Establishment:** A new I/O device chooses the best parent(s) based on the *candidate router table* statistics and the *routers’ rank in RPL*. To provide reliable routing, each I/O device chooses the two best routers as its RPL
parents. During the normal network operation, an I/O device might need to change the routers to cope with possible changes in the network. In that case, the I/O device can still use the earlier mentioned information to select the two best routers. The I/O device, upon selecting the RPL parents and joining the RPL, starts to send the DAO message to its potential parents to construct the down path in the network. The routers then update the routing information in their tables.

**Contract or end-to-end connection establishment:** An I/O device sends setup messages including its traffic characteristics to both selected routers to communicate with the potential destination (gateway or actuator). The routers forward these same setup messages to the requested destination along the established multipath routes by RPL to reserve resources for real-time communication.

In case of network disturbance (e.g., lack of power, bad channel condition, etc.), an I/O device might decide to change parent. In that case, the router should determine whether it considers the device as being removed or not based on a timeout mechanism [79].

**Data publication:** The I/O device, as a sensor node, publishes its sensor data toward an actuator or gateway. The I/O device uses the selected RPL parent(s) to deliver the data toward the final destination.

### 4.5 Performance evaluation of ISA100.11a* and D-MHR

To evaluate the performance of ISA100.11a* and D-MHR in terms of communication reliability, latency and management efficiency, we simulate each of these networks in NS-2 simulator where 25 systematically deployed infrastructure nodes (1 gateway, 2 access points, 22 routers) and 38 randomly deployed I/O devices are considered in a 100m × 100m area. The transmission range of the nodes is set to 15m. We consider that 1 data packet is generated by an I/O device in every 4s, while a management packet is generated in every 2s. The data rate considered during the simulation is 15 Kbps. For the comparison with centralized systems, we also simulate an ISA100.11a network with the same setup.

#### 4.5.1 Reliability and real time communication guarantee

To evaluate the communication reliability and latency of the proposed schemes, external interference has been inserted by dropping the link quality between I/O devices and routers in the network. As a reaction, the packet delivery ratio drops immediately in all of the three networks as shown in Figure 4.8 (top).
delivery ratio in ISA100.11a network drops below 40% and remains low for a while until the central SM fixes the broken links. ISA100.11a* and D-MHR networks are also affected by the disturbance where packet delivery ratios have gone down up to 60% and 85% respectively. However, ISA100.11* recovers 6 times faster than the standard ISA100.11a while D-MHR can even fix it 10 times faster than the standard ISA100.11a.

Figure 4.8 (bottom) shows the consecutive packet arrival time at the gateway for ISA100.11a, ISA100.11a* and D-MHR, which varies around 4 seconds (same as the I/O data rate) during normal operations. As soon as external interference is applied, the packet arrival interval explodes (with a delay up to 50 seconds) in ISA100.11a network. While ISA100.11a* and D-MHR networks are also affected by the disturbances, these networks experience 45% and 75% lower delays in packet reception respectively than that of ISA100.11a. In addition, ISA100.11a remains in the unstable state much longer than ISA100.11a* (1.6 times) and D-MHR (2.7 times) as the SM in ISA100.11a has to repair the broken links upon receiving periodic neighbor diagnostic reports, which takes time. On the other hand, in ISA100.11a* and D-MHR, the I/O devices can use their local statistics to fix the problem, which improves the
reliability and guarantee low communication latency.

### 4.5.2 I/O joining efficiency

To evaluate the efficiency of I/O joining process in ISA100.11a* and D-MHR networks, we consider the overhead and delay of reserving management resources. Figure 4.9 shows the joining delay and overhead of ISA100.11a* and D-MHR in comparison to that of ISA100.11a. It is noticeable that both the joining delay and communication overhead are increased significantly in an ISA100.11a network as the hop distance increases. In contrast, in ISA100.11a* and D-MHR networks, these seem to be independent from the corresponding I/O’s distance to gateway. Moreover, the I/O devices in ISA100.11a* and D-MHR networks have at least 50% lower joining overhead than that of traditional approach. The reason behind this improved joining efficiency is the local join response from the routers. The proposed approaches can perform far better than traditional ISA100.11a approach in large-scale networks. These approaches can also better support harvester powered I/O devices. Note that the physical channel scanning period to detect advertisement is not considered in this evaluation.

![Figure 4.9: I/O joining delay and overhead.](image-url)
4.5.3 End-to-end connection establishment between I/O devices

To evaluate the performance of the proposed approaches in terms of delay and communication overhead to establish connections between I/O devices, we grouped the I/O devices based on the distance between the source and destination via the gateway for fair comparison.

In this experiment, we disabled the over-provisioning policy so that no resources are readily available for the routers in the mesh network to support traffic of I/O devices. We separately measure the communication overhead and delay of ISA100.11a* approach for reserving the communication resources between I/O devices and their selected routers (ISA100.11a* local reservation), and between routers and gateway (ISA100.11a* mesh reservation). Figure 4.10 displays the results of the end-to-end connection establishment delay and overhead. As expected, hop distance increment (between source and destination) increases the delay and communication overhead to establish connections in ISA100.11a and ISA100.11a* networks due to their centralized resource reservation scheme. However, the delay and overhead to reserve local resources for I/O devices in ISA100.11a*, do not have any impact on the distance between source and destination as they only need to communicate with the
4.5 Performance evaluation of ISA100.11a* and D-MHR

routers in one hop neighborhood. If we allow over-provisioning and resources are readily available in the mesh network, the overall delay and overhead to establish end-to-end I/O connections in ISA100.11a* come close these local reservation values. As a result such connections can be made thrice as faster with 80% lower overhead than that required in an ISA100.11a network.

The end-to-end connection establishment delay and overhead in D-MHR do not increase if the network scales up due to its distributed approach (D-SAR signaling protocol). The communication overhead in this case is slightly higher than the ISA100.11a* local reservation as the routers have to schedule resources in this case after receiving the connection request from I/O devices. However, D-MHR outperforms ISA100.11a* and ISA100.11a when the over-provisioning policy is turned off (i.e., ISA100.11a* having mesh reservation).

4.5.4 Disturbance recovery

In case of network disturbances, such as edge failure between I/O devices and routers due to interference, the I/O devices might have to re-join the network or find a new router. To recreate such scenarios, we introduce edge failures by reducing the packet reception rates of the links between I/O devices and their parents in different parts of the network. Finally, we calculate the delay and number of messages required to fix these issues in ISA100.11a, ISA100.11a* and D-MHR networks. Figure 4.11 shows the behaviors of these networks in the case of edge failures between I/O devices and their respective parents.

The central SM of ISA100.11a chooses two routers for each node (I/O device or router) to increase reliability in the network. In event of disturbances, the routers in traditional ISA100.11a send connectivity alert to the SM which in turn configures new routers and resources to the I/O devices. On the contrary, an I/O device in ISA100.11a* and D-MHR can choose an alternative router according to its OFs and send a join request to the new router. After getting connected, the I/O device can use the previously allocated resources of that router in ISA100.11a* while in D-MHR, the D-SAR signaling protocol reserves the communication resources on the multipath route towards the gateway to enable reliable and real-time communication with the rest of the network.

Figure 4.11 shows that the hierarchical management scheme of ISA100.11a* can achieve 2-4 times lower delay and 5-15 time lower overhead compared to that of ISA100.11a when recovering from edge failures in a multi-hop network. D-MHR also provides similar performances sometimes even with lower delay and overheads to establish I/O connections in the network.
4.6 Concluding remarks

Existing industrial technologies such as ISA100.11a and WirelessHART do have mechanisms (e.g., blind channel hopping, multipath routing, etc.) to provide reliable communications in an industrial environment. However, due to the use of a centralized network management approach, these systems take a long time to fix network disturbances. In addition, such systems are not capable of supporting resource constraint devices. To address these issues, we first present a hierarchical centralized network management approach named ISA100.11a* where a central SM controls the routers in the mesh network while part of the communication resources are delegated to the routers to address the requirements of the I/O devices locally. We evaluate the performance of ISA100.11a* in terms of different matrices such as communication reliability, latency, management efficiency, by comparing those of traditional ISA100.11a approach. We found that it responds to the network disturbances faster with lower communication overhead. In addition, we found that the I/O joining delay and overhead in ISA100.11a* are not scale up with the network scale because of having direct join responses from the routers. Thus, ISA100.11a* can
better support the resource constraint I/O devices when compared with the existing centralized industrial systems. The centralized control of ISA100.11a* also make it suitable for the applications where a global system overview is required.

Although having the above mentioned potential, ISA100.11a* can not reuse the communication resources due to its centralized scheduling approach, which restricts it from scaling up. To address this issue, we propose a hierarchical network management approach named D-MHR for industrial applications requiring higher scalability. D-MHR allocates the communication resources distributively among the routers in the mesh network while the I/O devices get their resources allocated by the routers. The I/O devices in D-MHR do not need to have enough resources that is usually required to participate in a distributed network. D-MHR applies the spatial reuse of communication resources, which improves the network throughput in a large scale-network. We found that D-MHR can fix the broken links with I/O devices in the network much faster than the ISA100.11a and ISA100.11a* approaches. The connection establishment between I/O devices in a D-MHR network takes much shorter time and has lower overheads when compared with those in ISA100.11a and ISA100.11a* networks. Similar to ISA100.11a*, the response time and communication overheads during I/O joining are not related to the network scale in D-MHR approach. In addition, it is not prone to the central SM manager node failure thus can better address the industrial applications in a dynamic environment.
Energy harvested technologies have brought a paradigm shift in the industrial automation sector by procreating self-powered wireless input/output (I/O) devices. Unfortunately, current wireless technologies for industrial applications, such as WirelessHART and ISA100.11a, are yet far from supporting harvester powered I/O devices. Some attempts have been made to support harvester powered I/O devices in deterministic networks by reducing their energy consumption during steady-state phase. However, the network joining phase is not discussed in any of these works, which usually consumes a significant amount of energy.

This chapter analyzes both the network joining and the steady-state phases to understand the real challenges of energy harvested communication. After that, an energy efficient network joining scheme is proposed for the I/O devices. The proposed scheme can reduce the network joining delay significantly when compared with the traditional ISA100.11a joining scheme. We also propose a reliable data transmission scheme for harvester powered I/O devices by utilizing spatial diversity that outperforms ISA100.11a data publication in terms of packet reception rate. Finally, an asynchronous data publication scheme is proposed for the I/O devices with strict energy budget that allows the I/O devices to publish data according to their energy supply.

Partially based on:

5.1 Introduction

To design long lasting maintenance free industrial systems, energy harvesters are becoming popular as an alternative power source for industrial I/O devices. However, present-day energy harvesters can generate only a small amount of energy, which allows the I/O devices to transmit/receive very limited number of packets per reporting cycle. The amount of harvested energy also varies over time depending on the ambiance of the factory (e.g., amount of light/vibration). As a consequence, harvester powered I/O devices face many practical challenges in an industrial network [16].

Due to the deterministic resource reservation, I/O devices in the widely used industrial stems such as WirelessHART and ISA100.11a, have to follow complex network joining process and security mechanisms before being able to publish their data [81,82]. Harvester powered I/O devices cannot afford these power hungry procedures due to their limited energy budget. Thus, this type of I/O devices may frequently lose their connectivity/synchronization when operating in the above mentioned industrial networks. Alternatively, the harvester powered I/O devices may publish data by forming an ad hoc network whenever they gather sufficient energy. Such contention based communications do not require time synchronization between network devices. However, these systems are not suitable for time critical industrial applications as they cannot guarantee reliable communication.

Although several works have been conducted to address the requirements of energy harvested I/O devices, most of those have focused on minimizing the I/O energy consumption during the steady-state phase of the network [16,36,83]. The energy consumption during network joining that consumes a significant amount of energy, is overlooked in these works. In this chapter, we therefore analyze the I/O energy consumption in ISA100.11a network during the joining phase in addition to that in normal operation to better understand the challenges of energy harvesting communications. Based on this analysis, we classified the energy harvested industrial wireless sensor networks (EH-IWSNs) into two categories based on their applications. In the first category, the I/O devices are expected to have periodic data traffic. However, the main difference of this EH-IWSN with traditional industrial network is the scarcity of energy, as I/O devices in this network are powered by energy harvesters possibly in addition to batteries. The second category includes such networks where the I/O devices are only powered by energy harvesters and engaged in event-based data transmission for non-critical monitoring.

We propose an energy efficient network joining scheme to support harvester powered I/O devices that belong to the first category EH-IWSNs. We also propose
5.2 I/O energy consumption in ISA100.11a network

The energy consumption of different types of transmissions and receptions in ISA100.11a are calculated by using the method proposed in [32], which takes the timing inputs from the ISA100.11a timeslot structure shown in Figure 5.1. Below, we derive the energy consumption for these message types in ISA100.11a network, which can be used to calculate the energy consumption in other networks by small modifications. Let us denote the transmit power as $P_{Tx}$ and the receive power as $P_{Rx}$.

![Figure 5.1: Timeslot structure in ISA100.11a/IEEE802.15.4e (TSCH mode).](image)

To transmit any packet to a specific receiver, an acknowledged transmission is
used, which consumes,

$$E_{Tx} = Ts_{CCA} \times P_{Rx} + Ts_{MaxTx} \times P_{Tx} + Ts_{Ack} \times P_{Rx}. \quad (5.1)$$

However, a failed transmission (no acknowledgment received after the transmission) consumes,

$$E_{FailTx} = Ts_{CCA} \times P_{Rx} + Ts_{MaxTx} \times P_{Tx} + Ts_{AckWait} \times P_{Rx}. \quad (5.2)$$

Similarly, to receive a (data) packet from a specific transmitter, a receiver uses an acknowledged reception that consumes,

$$E_{Rx} = Ts_{MaxTx} \times P_{Rx} + Ts_{Ack} \times P_{Tx}. \quad (5.3)$$

An idle reception is used when a receiver expects to receive a packet but there is no packet to receive. In this case, the reception is aborted after the time-out and such reception consumes,

$$E_{Idle} = Ts_{RxWait} \times P_{Rx}. \quad (5.4)$$

To receive an advertisement, a receiver consumes (no acknowledgment required),

$$E_{Adv} = Ts_{MaxTx} \times P_{Rx}, \quad (5.5)$$

whereas, the required energy consumption during a failed advertisement reception is

$$E_{FailAdv} = Ts_{RxWait} \times P_{Rx}. \quad (5.6)$$

The total energy consumption of an I/O device comprises of the energy consumption in the joining phase and the steady state phase, which are further discussed below.

### 5.2.1 Energy consumption during network joining phase

During the network joining, the radio of an I/O device has to be turned on continuously throughout the whole scanning period, which consumes a significant amount of energy. The energy consumption of an I/O device to scan $N_{scn}$ slots on $N_{ch}$ channels is

$$E_{scan} = N_{ch} \times N_{scn} \times T_{slot} \times P_{Rx}, \quad (5.7)$$

where the slot duration is $T_{slot}$. After receiving advertisements in the scanning phase, an I/O device sends a join request to the proxy router and receive links and frames from SM as described in Section 4.2.1.3. Thus, the total energy required for an I/O
5.3 Energy efficient I/O joining and reliable data publication

Device to join an ISA100.11a network is

\[
E_{\text{join}} = E_{\text{scan}} + E_{\text{Tx}} + \left( N \times E_{\text{FailAdv}} + E_{\text{Rx}} + E_{\text{Tx}} \right) + M(N \times E_{\text{Rx}} + E_{\text{Tx}}),
\]

where, the value of \( N \) depends on the number of hops between the I/O and the SM and \( M \) depends on the number of neighbors (routers) from which the I/O device can receive advertisements. Note that, the major portion of the joining energy is spend on the scanning phase.

5.2.2 Energy consumption during steady state phase

Energy consumption of an I/O device during normal operation depends on its publishing period and the advertisement rates of the neighboring routers. Thus, the average energy consumption of an I/O device over a fixed interval is

\[
E_{\text{IO}} = E_{\text{Mgt}} + E_{\text{Data}},
\]

where, \( E_{\text{Mgt}} \) is the energy consumption to receive periodic advertisements and \( E_{\text{Data}} \) is the energy consumption for data transmission during this period. \( E_{\text{Mgt}} \) and \( E_{\text{Data}} \) can be calculated by using the equations 5.10 and 5.11 respectively, where \( N \) represents the number of a particular type of messages during the fixed interval (e.g., \( N_{\text{RecAdv}} \) is the average number of received advertisements).

\[
E_{\text{Mgt}} = N_{\text{RecAdv}} \times E_{\text{Adv}} + N_{\text{FailAdv}} \times E_{\text{FailAdv}}.
\]

\[
E_{\text{Data}} = N_{\text{RecPkt}} \times E_{\text{Tx}} + N_{\text{FailPkt}} \times E_{\text{FailTx}}.
\]

5.3 Energy efficient I/O joining and reliable data publication

I/O devices in ISA100.11a have to go through an energy consuming joining phase which makes it challenging for harvester powered I/O devices to work efficiently in this network. To make ISA100.11a suitable for resource constraint devices, in this section we propose an improved I/O joining scheme that can make the network joining phase affordable. Later, we propose a reliable data publication scheme for such I/O devices that can reduce the packet re-transmissions in the network.
5.3.1 Improved I/O joining

The I/O devices in ISA100.11a scan each available channel sequentially for a fixed period \(N_{scn}\) slots to receive advertisements. During the scanning phase, an I/O device might receive multiple advertisements from different routers, although discovering one router is enough for initial communications with the SM. Such scanning scheme consumes a significant amount of the energy during I/O joining as discussed in Section 5.2. Thus, the following options are considered in this work to improve the traditional ISA100.11a scanning scheme.

- Option 1: Each I/O device scans the available channels sequentially similar to the traditional ISA100.11a scanning approach; i.e., the I/O devices always start scanning from Channel 11 and stay not more than \(N_{scn}\) slots on a particular channel. However, the scanning process is terminated as soon as \(N_{dis}\) routers are discovered or maximum scanning interval \(T_{scn}\) is passed. I/O devices with limited energy budgets use \(N_{dis} = 1\) to discover a router for initial communications with the SM, while \(N_{dis} > 1\) can be used when the I/O devices have adequate energy as discovering more routers gives more options to an I/O device for initial communications with the SM.

- Option 2: Each I/O device scans the available channels randomly, i.e., each I/O device chooses a random channel independently from the available set and scans \(N_{scn}\) slots before moving to the next channel. As soon as \(N_{dis}\) routers are discovered or maximum scanning interval \(T_{scn}\) is passed, the scanning process has been terminated.

- Option 3: Each I/O device scans a random channel on each slot and as soon as \(N_{dis}\) routers are discovered or maximum scanning interval \(T_{scn}\) is passed, the scanning process has been terminated.

The above mentioned approaches can reduce the scanning time a bit when compared to the traditional ISA100.11a scanning. However, still the I/O devices have to scan all of the 16 channels of IEEE802.15.4, which takes significant time and energy. We can use a subset of channels for advertisement broadcast to shorten the scanning time even further, where these channels can be chosen according to the radio environment of the network. In this work, we choose only the three IEEE 802.15.4 channels that are non-overlapping with the frequently used WiFi channels for advertisement broadcasts.\(^1\) This makes the joining faster and affordable for the harvester powered I/O devices. A different hopping pattern containing the three respective

---

\(^1\) We believe three channel allows sufficient choices for advertisement broadcast as well as reducing the scanning burden from the I/O devices.
5.3 Energy efficient I/O joining and reliable data publication

channels is therefore considered for advertisement broadcast, while the regular hopping pattern is used for data communication. To efficiently use these two different hopping patterns, we divide the superframe into two parts as shown in Figure 5.2. The first part is reserved only for advertisement broadcast and the second part is for actual communication. Higher number of slots in the advertisement period provides higher scalability in the network. However, it reduces the effective throughput of the network as fewer slots are available for actual communication. This issue can be addressed by increasing the length of superframe.

5.3.2 Spatial diversity approach (SDA) for reliable data publication

ISA100.11a standard utilizes blind channel hopping to increase communication reliability, where packet transmissions between the same pair of devices (i.e., I/O device-router, router-router) take place over different physical channels in every instance. However, some packets may still subjected to deep fading of industrial harsh environment and need to be re-transmitted. This costs additional energy and increase communication latency. To reduce these packet re-transmissions and latency, we utilize spatial diversity by using the built-in multiple paths of ISA100.11a. Instead of transmitting packets to a randomly selected neighboring router from a set of two best routers as suggested in a traditional ISA100.11a, the I/O devices in our approach send the copies of same packet to both routers. As these paths are independent from
each other, the redundant copies of most packets overcome fading issues which increases the packet reception rate. Transmission of redundant packets in every transmission consumes almost double energy when compared with the ISA100.11a transmission policy. To reduce this overhead, the I/O devices only transmit redundant packets when it is necessary according to the following steps.

- **Step 1:** An I/O device always transmits the packets to the router which can be communicated earlier (scheduled in an earlier slot by the SM).
- **Step 2:** The second copy will only be transmitted (to another router) if the first transmission fails.

While improving reliability, this scheme can reduce the network traffic. Although additional energy is consumed for these extra transmissions, the overall increase in energy consumption is not significantly higher than that required for re-transmitting the failed packets in traditional ISA100.11a. Moreover, this approach can be employed locally by turning on only when an router reports significant packet losses from an I/O device and turning off when both copies of the packet are successfully received for a while. The I/O devices do not need to consider complete disjoint paths as the second copy of a particular message is only transmitted if the first copy fails. Thus, no significant changes in the ISA100.11a stack is needed to apply this scheme.

### 5.3.3 Evaluation of the proposed I/O joining and data publication schemes

To evaluate the performance of the proposed approaches in this chapter, we consider 50 industrial networks, each of which consists of 40 uniformly distributed I/O devices and 16 systematically deployed routers in a 50 m × 50 m area. Such a deployment is shown in Figure 5.3. The routers broadcast advertisements with an interval varied between 0.25s to 4s. The I/O devices scan a particular channel for $N_{scn} = 40$ slots to discover one proxy router (i.e., $N_{dis} = 1$). The maximum scanning duration is fixed to $T_{scn} = N_{Ch} \times N_{scn}$ slots, where $N_{Ch}$ can be either 16 or 3 depending on the number of channels used for advertisement broadcast. The transmission power is varied between 0 to 12 dBm. The I/O devices publish their data in an interval between 250ms to 1s. While implementing the channel hopping mechanism in the ISA100.11a simulation, the following hopping pattern

$$hp_1 = 19, 12, 20, 24, 16, 23, 18, 25, 14, 21, 11, 15, 22, 17, 13, 26,$$

is considered, where the numbers represent the corresponding channel of IEEE802.15.4. A different hopping pattern, $hp_2 = 15, 20, 25$, containing the
IEEE802.15.4 channels which are non-overlapping with commonly used WiFi channels, is used for the advertisement broadcasts in our proposed fast joining scheme as discussed in Section 5.3.1. To make it easier, let us consider that the SM assigns a particular channel offset for all of the communications of a router including advertisement broadcasts. That means if channel offset 5 is assigned to a router, all the I/O devices want to communicate with that router have to follow the hopping pattern with offset 5.

To compare the RSSIs and packet losses, we consider the packet transmission and reception when all I/O devices are in the stable state. In total 50 different networks for each setup (combinations of different transmission power, advertisement rate, number of advertisement channels) have been simulated in MATLAB to generate statistically significant results, where the location of the routers are kept fixed while the I/O devices have different positions in different networks.

**Industrial channel propagation model**

The radio signals suffer from free space path-loss, multipath fading and shadowing in indoor environment. In an industrial environment, this scenario become even worse due to the presence of heavy machinery made of metals which eventually makes the industrial channels unpredictable. In this work we used the IEEE802.15.4a
channel model [84] to calculate the RSSI in the network which can be represented as,

\[
PL(d) = PL_0 + 10n \log_{10}(d) + Sh + SSF + \text{noise},
\]

where, \(PL_0\) is the free space unit path loss in dB (i.e., the loss after 1 m distance), \(n\) is the attenuation factor, \(d\) is the distance between a transmitter and receiver in m, \(Sh\) is the shadowing factor in dB and \(SSF\) is the small scale fading in dB. The noise is mainly added to achieve the time varying nature of the shadowing, which is a zero mean Gaussian random variable that varies over time. More specifically, noise \(\sim N(0, \sigma^2)\) dB.

Typically, for indoor home/office environment the shadowing effect is modeled as an uniformly distributed random number and the value of shadowing effect is considered as a constant for a transmitter-receiver pair during the communication period. However, in factory environments, the movement of the machinery, highly reflective materials and electric impulses due to friction or other reasons can trigger time varying shadowing effect typically known as temporal fading [85]. To replicate a similar industrial environment, we model the shadowing as a multivariate Gauss distributed random number, where the shadowing varies over different IO device and router pairs and also with the channel used for communication. Mathematically,

\[
Sh \sim N \left( \begin{bmatrix} \mu_{io} \\ \mu_{rou} \\ \mu_{ch} \end{bmatrix}, \begin{bmatrix} \sigma^2_{io} & \sigma_{io}\sigma_{rou} & \sigma_{io}\sigma_{ch} \\ \sigma_{rou}\sigma_{io} & \sigma^2_{rou} & \sigma_{rou}\sigma_{ch} \\ \sigma_{ch}\sigma_{io} & \sigma_{ch}\sigma_{rou} & \sigma^2_{ch} \end{bmatrix} \right),
\]

where, \(\mu\) represents the mean and \(\sigma\) represents the standard deviation of the distribution. The suffixes io, rou and ch represent I/O device, router and channel respectively. For the simulation, we set \(PL_0 = 56.7\) dB, \(n = 2.15\), \(SSF = 13\) dB, \(\mu_{io} = \mu_{rou} = \mu_{ch} = 0\) dB, \(\sigma_{io} = \sigma_{rou} = \sigma_{ch} = 6\) dB and \(\sigma_n = 0.01\) dB according to the suggestions of [84]. The receiver sensitivity, \(\gamma_{th} = -98\) dBm is selected based on the Nivis hardware specification [86].

**Results and discussion**

To evaluate the performance of the proposed fast joining approach and the spatial diversity approach of data publication, we conduct several experiments by varying the transmission power, number of channels for advertisements, advertisement and I/O publication rate, etc. We compare several performance matrices to discuss the potentials of proposed schemes overs traditional ISA100.11a schemes. We also identify the limitations of the proposed fast joining schemes.
5.3.3.1 Scanning time for I/O joining

Figure 5.4 provides a comparison on the average scanning time required in traditional ISA100.11a joining with that in our proposed fast joining approach. ISA100.11a joining requires at least 6.4 seconds of scanning (400 ms on each of the

16 channels in IEEE802.15.4) [23] while the proposed fast joining approach reduces this significantly (between 87%-97%) by introducing several thresholds mentioned in Section 5.3.1. In the proposed fast joining approach, the scanning time goes up with the increase in advertisement interval as the I/O devices have to scan longer to detect an advertisement successfully. However, limiting the advertisement broadcasts on three channels can reduce the scanning time even when the advertisements are broadcasted less frequently because in that case the I/O devices have to scan fewer channels and the density of advertisements per channel is higher than the case where all the 16 channels are used. Note that all the three options in proposed fast joining approach result in almost similar scanning times.
5.3.3.2 I/O joining outage

As we terminate the scanning process after a fixed scanning window, a number of I/O devices are failed to join the network during the prescribed period. The scenario become worse when the advertisements are broadcasted less frequently. The situation can be addressed partially by increasing transmission power which also can reduce the required scanning time for I/O joining. In Table 5.1, we presented the outage probability of I/O joining for different transmission power level and advertisement rate. Almost all of the I/O devices are able to discover a router during the scanning window with high advertisement rate (1 advertisement in every 0.25-0.5s) regardless of the transmission power and number of advertisement channels while a significant outage is observed with lower advertisement rate. These results suggests that at least a moderate advertisement broadcast rate (1 advertisement/s) needs to be used for the success of our proposed energy efficient fast I/O joining scheme.

<table>
<thead>
<tr>
<th>$P_{Tx}$ [dBm]/Adv.interval [s]</th>
<th>0.25</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>2.7</td>
<td>5.1</td>
<td>24.1</td>
<td>48.1</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>6.3</td>
<td>26.5</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>4.9</td>
<td>18.5</td>
</tr>
</tbody>
</table>

5.3.3.3 RSSI and packet loss probability

The I/O devices start publishing data according to their publishing periods as soon as the SM assigns communication resources for them. Some of these data packets fall into deep fading in harsh industrial environment. We monitor the health of the received packets in the network by calculating their RSSI. Figure 5.5 shows the cumulative distribution functions of RSSIs with different transmission power levels and number of scanned channels for both schemes. Around 38% of the received packets fall below the threshold of error-less detection in the network utilizing ISA100.11a data publication approach when the transmission power is set to 0 dBm. On the other hand, the proposed SDA out performs ISA100.11a approach of data publication by achieving higher packet reception rate in every scenario. We are able to reduce down the packet loss probabilities from 38% to 14.5%, 12% to 1.5% and 6% to 0.4% by using SDA data publication with transmission power 0dBm, 9dBm and 12dBm respectively. Note that no re-transmission policy is implemented in our simulation for fair comparison.
5.3 Energy efficient I/O joining and reliable data publication

5.3.3.4 Energy consumption

The energy consumption of any network depends on the hardware specifications as well as the communication protocol. In this chapter we consider the specifications of Nivis VarsaNode 210, whose transmission power is 180 mW (when transmitting at 12 dBm) and reception power is 63 mW. To calculate the average energy consumption of the I/O devices in the steady-state phase (when the network is in stable condition), we have to consider packet transmissions and advertisement receptions for a fixed period. Results from 5 minutes of network simulation in the steady-state phase is presented in this chapter. On the other hand, the joining energy consumption is independent of this period and only required during the network (re-)joining. This portion of the energy has to be harvested at first so that the nodes can (re-)join the network. The proposed fast joining scheme can reduce up-to 95% (when advertisements are broadcasted on 3 channels with 0.25s interval and 12 dBm transmission power is used) of energy consumption required in traditional ISA100.11a joining, as shown in Figure 5.6. The comparison of I/O energy consumption in the steady state phase between the networks utilizing ISA100.11a approach and proposed spatial diversity approach are shown in Figure 5.7. The energy spend during the steady-state phase comes from two different parts: energy to receive advertisement and the energy for actual data communication. The first part somehow depends on the
advertisement broadcast interval, which is calculated assuming that I/O devices attempt to receive all the advertisements from two neighboring routers. However, an I/O device does not need to receive all the advertisements from all its neighboring routers to maintain synchronization, instead it can be selective when the available energy level is critically low. The energy consumption for data communication depends on the publishing periods of I/O devices. In our proposed scheme with spatial diversity, data communication energy is naturally higher than that in traditional ISA100.11a due to the redundant packet transmissions. However, with our scheme less re-transmissions are required whereas traditional ISA100.11a results in much higher re-transmissions, which will cost additional energy (ignored in this calculation).

5.4 Asynchronous communication schemes for I/O devices with strict energy budget

The fast I/O joining scheme proposed in the previous section reduce the joining overhead significantly which makes the network better suited for resource constraint I/O devices. However, the I/O devices still have to scan the physical channel to join the network by detecting advertisements. Inspired by the advances in the energy harvesting technologies, many industrial applications are trying to achieve the fit
5.4 Asynchronous communication schemes for I/O devices with strict energy budget

and forget attitude. That means, such I/O devices may only be powered by energy harvesters. Thus, these I/O devices might often do not have the energy to follow complex joining and security mechanisms of the industrial systems. One of the solutions can be the use of contention based communications for the data publication of these I/O devices, where harvester powered I/O devices will transmit their data as soon as they harvest sufficient energy. The routers have to listen continuously to detect such data packets from the I/O devices. While the routers may afford such overheads in an industrial environment due to the possibility of systematic placement near to power supply, contention based mechanisms cannot fulfill the timing and reliability requirements of the industrial applications which is discussed previously in Chapter 2. In addition, for battery powered routers it is not practical to keep their radio on for a long duration. Thus, a combination of contention free and contention based communication systems can best address this scenario. The traditional ISA100.11a standard uses such an approach by utilizing slow hopping period occasionally for neighbor discovery as well as to allow I/O devices to join the network quickly.

The network joining scheme which utilize the slow hopping period in ISA100.11a is known as active joining scheme, where I/O devices with imprecise synchronization place solicitations during the slow hopping period and listen for advertisements on the next slot to join the network. The routers place advertisements immediately on

Figure 5.7: Comparison of I/O energy consumption during 5 minutes in the steady-state phase.
the next slot after receiving solicitations from the I/O devices. I/O devices using active joining scheme do not have to spend energy on idle listening. However, to use this scheme, I/O devices need to have the superframe synchronization so that they know when the routers will start listening i.e., the start time of the slow hopping period. Failure to have this superframe synchronization can cause collision with scheduled communications during the slotted hopping period, which is not acceptable. Thus, this scheme is not appropriate for the harvester powered I/O devices we are targeting. In response, we propose an asynchronous communication scheme for the harvester powered I/O devices that can co-exist with the industrial networks designed for real-time monitoring and control applications.

5.4.1 Proposed asynchronous communication scheme

To support scheduled communication and contention based communication in the same system, we divide the superframe into two parts where the first part is used for dedication communications between network devices and the second part is used by the harvester powered I/O devices to broadcast their data asynchronously. To let the I/O devices capable of operating without any synchronization, we implement the following policies.

1. The position of the slow hopping period in a superframe is distributed spatially. That means neighboring routers use the slow hopping period at different times which allow the I/O devices to transmit their data without having superframe synchronization.

2. Slow hopping periods in the proposed scheme use different channel hopping pattern than that of slotted communication period in the superframe. These two hopping patterns do not use any common physical channels to guarantee that the asynchronous data packets wont collide with the scheduled communications even if the harvester powered I/O devices do not have superframe synchronization.

The ratio between slotted hopping duration and the slow hopping duration depends on the traffic pattern and the number of harvester powered I/O devices. Similarly, the number of physical channels used during these period depends also on the above mentioned factors as well on the router density in the network. Allowing more channels in the slow hopping pattern improves the packet reception probability of the I/O devices utilizing asynchronous data publication. However, the router density in the network should also be increased accordingly to be able to detect I/O data packets placed on any of the slow hopping channels. There should be at least a router in
range of a harvester powered I/O device, listening on the exact channel used by the I/O device.

To give an intuitive example of the proposed asynchronous communication scheme, let us consider a network with few I/O devices and routers as shown in Figure 5.8 (top left). The I/O device in range of Router 1, Router 2 and Router 3 is utilizing asynchronous communication to publish its data. To be able to detect such data packets the routers divide their superframe into two parts as mentioned earlier. Note that Router 1, Router 2 and Router 3 are using slow hopping period at different moments in the superframe. Collaboratively, these three routers listen for asynchronous data during the whole superframe period which increase the communication reliability in the network.

**5.4.1.1 Packet collision and capture effect**

As the I/O devices utilizing asynchronous communication scheme do have slot and superframe synchronization, data packets from such I/O devices may collide with each other, which is unacceptable in industrial applications. To reduce such scenarios, the harvester powered I/O devices in our scheme use a short CCA to check the channel before data transmission. However, collision may still occur due to uncoordinated transmission instances. In Figure 5.9, we illustrate some of these scenarios, where two harvester powered I/O devices are trying to transmit their packets of the

![Figure 5.8: Sample network with harvester powered I/O devices (top left), superframe structure to support asynchronous communication scheme (right).](image)
same channel. In case 1, the I/O devices are using two consecutive slots for communication similar to the ideal scheduled communication in slotted hopping, thus no collision happens. Nevertheless, as these I/O devices do not have any idea about the slot start times, they can initiate packet transmissions at any time which is shown in case 2-5. In case 2, the second I/O aborts its transmission as the channel is used by other device. In case 3, the second I/O performs its CCA while the first I/O is in transition to switch its radio for transmission. Due to the typical hidden terminal problem, collision is unavoidable here. In case 4, although the second I/O first gets a free channel, later it finds the channel busy, thus abort its transmission. An interesting thing happens in case 5, where the second I/O performs the CCA just before the first I/O starts to transmit. In this case, the receiver (router) starts decoding the packet from first I/O but the packet from second I/O may take over when the signal strength of the two packets differ by at least 3dB. This phenomena is known as capture effect [87,88].
To evaluate the proposed asynchronous communication scheme, we consider a setup which contains both the regular I/O devices required to have real-time communications and only harvester powered I/O devices for non-critical applications in the same network. The simulations are carried out with 10 routers, 30 regular I/O devices and 10 harvester powered I/O devices in a 50 m × 50 m area as shown in Figure 5.10.

Two different superframe length (0.75s, 1s) are considered in the simulation. Each router broadcasts an advertisement in every superframe to allow the regular I/O to join in the network. In the superframe 0.25s period is reserved for slow hopping to allow the harvester powered I/O devices to publish their data. This slow hopping period are started at different times in the superframe among the neighboring routers as explained in Section 5.4.1. Two transmission power levels (12 and 0 dBm) are used to check the performance of the proposed scheme in high and low power scenarios. For fair comparison, same data publication period, one packet per superframe, is set for the regular and harvester powered I/O devices. The regular I/O devices use this rate for periodic traffic by using dedicated slots in the superframe.
while the harvester powered I/O devices generate event based traffic according to this rate and place these packets randomly during the slow hopping period when the channel is free. The following hopping pattern

$$hp_3 = 19, 12, 20, 24, 16, 23, 18, 25, 14, 21, 11, 15, 22, 17, 13,$$

is considered during the slotted hopping period of the proposed approach, where the numbers represent the corresponding channel of IEEE802.15.4. A different hopping pattern, $$hp_4 = 26,$$ is used during the slow hopping period.

We consider the channel model explained in Section 5.3.3 for the simulation. We also consider a random bias, $$d \sim U(-5, 5)$$ ms with the slot starting time of the I/O devices using slow hopping pattern to recreate slot imperfection that takes place in real networks using slotted-CSMA.

To compare the RSSIs and packet losses, we consider the packet transmission and reception when all I/O devices are in the stable state. In total 50 different networks for each setup (combinations of different transmission power, advertisement rate, no of advertisement channels) have been simulated in MATLAB to generate statistically significant results, where the location of the routers are kept fixed while the I/O devices have different positions in different networks.

Results and discussion

5.4.2.1 Performance evaluation

To evaluate the performance of the proposed scheme, we quantify several performance matrices such as packet loss probability, aborted transmissions, packets received due to capture effect and the data packets received by multiple routers. All of these performance matrices shown in Table 5.2, are normalized against the number of packets transmitted in respective scenarios.

Table 5.2: Performance comparison of asynchronous communication scheme in terms of different matrices.

<table>
<thead>
<tr>
<th>Performance matrix</th>
<th>Tx power</th>
<th>0dBm</th>
<th>12dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$l_{sf} = 0.75s$</td>
<td>$l_{sf} = 1s$</td>
<td></td>
</tr>
<tr>
<td>Aborted transmission (%)</td>
<td>4.35</td>
<td>2.94</td>
<td>5.42</td>
</tr>
<tr>
<td>Capture effect (%)</td>
<td>1.36</td>
<td>0.82</td>
<td>5.87</td>
</tr>
<tr>
<td>Data received by multiple routers (%)</td>
<td>45.5</td>
<td>33.16</td>
<td>92.82</td>
</tr>
</tbody>
</table>

$l_{sf}$ denotes the superframe length.
Table 5.3: Comparison of packet loss ratios (%) in ISA100.11a and proposed asynchronous communication scheme.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>0dBm</th>
<th>12dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traditional ISA100.11a</td>
<td>38.53</td>
<td>6.41</td>
</tr>
<tr>
<td>Asynchronous communication scheme</td>
<td>15.43</td>
<td>1.32</td>
</tr>
</tbody>
</table>

\( l_{sf} \) denotes the superframe length.

Packet reception rate

Upon powered on, the harvester powered I/O devices start publishing their data while the regular I/O devices start publishing after the SM assigns communication resources for them. Around 38% of the regular I/O packets are lost in the network ISA100.11a when the transmission power is set to 0 dBm. In spite of using contention based mechanisms, the proposed asynchronous data publication scheme also achieves similar success rates with a superframe length of 1s as shown in Table 5.3. Surprisingly, the proposed scheme outperforms the scheduled communication of ISA100.11a while using a superframe length of 0.75s. The reason behind this is the increased probability of having multiple routers listening during all parts of the superframe. As the routers in our simulation do not coordinate to select their slow hopping period, having a higher superframe length (1s in this case) decreases the probability of multiple routers listening simultaneously. With higher transmission power (12dBm), excellent packet reception rates are achieved for both superframe length.

Aborted transmission

Due to the slot imperfections, I/O devices utilizing asynchronous data publication may initiate packet transmissions when other devices are utilizing the channel. By using a CCA check, we are able to stop up to 5.4% of such packet transmissions, which improves reliability in the network.

Capture effect

In spite of initiating packet transmission on the same channel at the same time, some of the data packets from harvester powered I/O devices are received properly by the routers due to the capture effect phenomena explained in Section 5.4.1.1. Up to 5.4% packets are received successfully due to this effect in our simulation.
Data received by multiple routers

A significant portion of the I/O data packets during the slow hopping pattern has been received by multiple routers in the network. For low transmission power up to 45.5% of the packets are received by multiple routers while with high transmission power this goes even up to 93%. The redundant packets will not be forwarded further when detected by an intermediate router in the mesh network.

5.4.2.2 Energy consumption

The novelty of the proposed asynchronous communication scheme for harvester powered I/O devices lie in its ability to spend very little amount of energy for data communications. The proposed scheme does not have any management overhead. That means, the harvester powered I/O devices in this scheme only spend energy for data transmission. In Figure 5.11, we compare the average energy consumption of an I/O device in a network following traditional ISA100.11a approach, fast-joining scheme and asynchronous communication scheme respectively. The energy is calculated by considering the communications during 300 seconds in the steady state period. In the traditional ISA100.11a network and the networks utilizing fast I/O joining scheme, we consider that an I/O device spend energy for one network joining phase and never get disconnected from the network. While the fast joining scheme proposed in Section 5.3 can significantly reduce the energy spend for I/O joining, the proposed asynchronous scheme can reduce the total energy consumption even further (around 62.5% less than traditional ISA100.11a). In addition, this
scheme does not suffer from the issues arise due to network dis-connectivity.

5.5 Concluding remarks

This chapter analyzes the energy consumption of the I/O devices in different phases of communication to check the feasibility of energy harvesting industrial communication. It is clear that even though measures have been taken to reduce the average energy consumption of existing wireless protocols, still the node joining phase remains expensive for the harvester powered devices. In response, we propose a fast node joining procedure that is able to reduce the joining energy significantly without sacrificing quality in most of the cases. In addition, our proposed spatial diversity scheme for data publication can achieve higher reliability and needs fewer packet re-transmissions in the network when compared with traditional ISA100.11a approach. This scheme is particularly suitable for harsh industrial environment where higher packet loss is expected. To realize a fit-and-forget system, we present an asynchronous communication scheme for the I/O devices with strict energy budget. The proposed asynchronous communication scheme can eliminate the network management overheads completely which makes the energy harvested communication implementable for real industrial applications.
This thesis contributed to making industrial wireless communication reliable for resource constraint I/O devices. It provided new insights into energy harvested industrial wireless networks. The solutions presented throughout the chapters have the potential to address the requirements of modern industrial applications. While these applications, including battery/harvester powered I/O devices, have distinct requirements, high communication reliability and low latency have to be guaranteed in all these cases. By applying different diversity schemes such as channel hopping and spatial diversity, reliable communication can be provided. We can provide low latency communication by modifying the network management schemes used by present-day industrial systems. In addition, I/O devices can publish their data in an energy efficient manner by using contention based communications. The proposed solutions can be applied in the existing industrial networks with small modifications.

This chapter first elaborates the main contributions and results of this thesis in Section 6.1. Then, Section 6.2 provides the overall conclusion of this thesis. Finally, we briefly describe the possible future research directions in Section 6.3.

### 6.1 Contributions

The contributions of this thesis to achieve reliable and energy efficient industrial wireless networking with resource constraint I/O devices can be summarized as follows.

While capable of supporting the monitoring applications fairly well, recently developed industrial wireless technologies such as WirelessHART and ISA100.11a are unable to address many requirements of modern industrial applications as identified in Chapter 2 of this thesis. For instance, due to the use of centralized resource management approach, these systems often face scalability problems. In addition,
these technologies are not designed to provide real-time communication with low latency, which is essential in time critical control applications. We found that the DECT standard have many features that can meet most of these requirements. As a response, we evaluated DECT standard in Section 3.3 for industrial monitoring applications that had to handle the diverse traffic pattern of dense IWSNs. Later in Section 3.4, DECT was evaluated for industrial control scenarios requiring reliable communications with low latency.

The centralized network management approach used by the current industrial wireless systems are unable to address the network disturbances in a real-time manner. In addition, the I/O devices in these systems have huge management overheads which consumes a large amount of energy. Thus, resource constraint I/O devices face numerous problems while operating in these systems. We designed and evaluated two hierarchical network management approaches in Chapter 4 that address the requirements of the I/O devices locally with low overheads as well as fixing the broken links quickly. To improve the power hungry node joining process of centrally managed industrial networks, we designed and evaluated an efficient network joining scheme for the resource constraint I/O devices in Section 5.3. Later, we proposed a data publication scheme for these I/O devices to improve their communication reliability in the network. Finally, to address the requirements of the I/O devices with strict energy budget by supporting opportunistic data publication based on their power supply, we designed and evaluated an asynchronous communication scheme in Section 5.4.

6.2 Concluding remarks

This thesis started with the aim to address the communication reliability and energy efficiency aspects of the industrial monitoring and control applications. In particular, we concentrated on the resource constraint I/O devices to allow them efficiently participate in the existing industrial networks. The main research question of this thesis was:

*How to provide energy efficient, real-time wireless communication between the I/O devices and the routers in an industrial network while improving communication reliability?*

To answer the research question, we analyzed the pros and cons of different industrial systems available today. We found that in spite of having several mechanisms to improve communication reliability, present-day industrial standards cannot support many requirements set by the modern industrial automation mainly due the to the rigid nature of these networks.

We can divide the industrial applications into two classes, namely monitoring
applications and control applications. Regardless of their differences, reliable communication guarantee is the most important requirement in both of these application classes. To address the research question from the communication reliability point, we first assumed that the network devices do not have energy constraints. We also considered that a star/tree network topology can best address the low latency communication requirement of industrial applications. We identified that DECT standard can support many of these requirements of industrial automation. Linked to this, we evaluated DECT for industrial monitoring applications where a highly scalable network should be supported. We conclude that DECT elegantly support the diverse traffic characteristics of a dense network comprising hundreds of I/O devices. The DCS mechanism of DECT is able to avoid internal interference by dynamically selecting better channels for communication. We then evaluated DECT for industrial control application where the main challenge is in proving low latency communication rather than achieving high scalability. We conclude that DECT is also able to maintain low communication latency due to its small timeslot and superframe duration. The dynamic channel allocation of DECT guarantees reliable communication in an industrial harsh environment.

The disadvantage of DECT is that it requires line powered infrastructure nodes and wired connection between those to maintain precise synchronization, which is not always feasible in an industrial environment. In addition, industrial networks often have to cover a large area that cannot be supported by a star network. Thus, recently developed industrial standards such as WirelessHART and ISA100.11a, use a mesh network topology. We found that the centralized network management approach used by these industrial standards largely affects the performance of the systems specially in a rapidly varying channel environment. These systems often impose high overheads and delays to cope up with network disturbances. In addition, harvester powered I/O devices, which are becoming popular in various industrial applications, face a lot of challenges such as power hungry joining, high management overhead, etc. in a centrally managed network. We stated the hypothesis that different network management schemes can be applied in the network and that a distributed/hierarchical management approach can better address the dynamic nature of industrial networks. At first, we validated this hypothesis by presenting a hierarchical centralized management scheme named ISA100.11a* where a centralized system manager controls the routers while blocks of communication resources have been delegated to the routers to address the requirements of the I/O devices locally. We evaluated the performance of ISA100.11a* in terms of communication reliability, latency, management overhead, network scalability etc., with respect to those of ISA100.11a which uses a centralized management scheme. The precondition set in
this evaluation was that I/O devices have resource constraints, which restricts them from participating in routing or distributed network management process, whereas the routers do not have strict energy budget due to the possibility of systematic placement, often close to the power sockets, in an industrial environment. Thus, routers can take care of the power hungry network management tasks such as routing, resource allocation, etc. We conclude that the routers in ISA100.11a* can quickly fix broken links with I/O devices as they do not have to report everything to the central system manager. The I/O devices also get faster response during network joining. Due to the centralized control, ISA100.11a* provides predictable behavior that makes it is suitable for the applications in which a global system overview is required without imposing additional management overheads on the I/O devices.

While having significant advantages over the centralized management approach, a hierarchical centralized management is also facing the network scalability issue similar to a centralized management as the communication resources can not be reused in these networks. Such systems are also vulnerable to the loss of the central system manager. For this reason, distributed management strategies are often preferred for networks that need to scale well and survive in dynamic channel environment. Nevertheless, the I/O devices often do not possess enough resources to run distributed management algorithms. To address these aspects, we designed a hierarchical distributed management scheme named D-MHR in which the neighboring routers negotiate on the communication resource scheduling, while the I/O devices get communication resources assigned from the respective routers without having a lot of management overheads. In D-MHR, routers can re-use the communication resources as long as they are two hop away from one another. From the performance evaluation of D-MHR in terms of communication reliability, latency, management overhead, network scalability etc., with respect to those of ISA100.11a and ISA100.11a*, we conclude that it can address the dynamic situation much faster and with lower overheads than the counter parts. In addition, D-MHR achieves higher scalability than ISA100.11a and ISA100.11a* by using communication resources in non-interfering parts of the network.

Although the hierarchical network management approaches make the industrial networks better suited for harvester powered I/O devices, they still need to join the network by detecting advertisements through energy consuming channel scanning. First, we stated the hypothesis that a network joining scheme with low overhead can make the industrial network suitable for harvester powered I/O devices. We validated this hypothesis by proposing an efficient network joining scheme for the I/O devices and evaluating its performance with the approach used in traditional industrial networks. We conclude that the proposed network joining scheme signifi-
cantly reduces the energy consumption during the network joining phase in comparison to ISA100.11a approach. We then proposed a reliable data publication scheme for these I/O devices that improves the communication reliability in the local networks between I/O devices and routers. This scheme helps to reduce the packet re-transmissions in the network and the energy spend on that purpose. We envisioned that some I/O devices in industrial applications may only be powered by energy harvesters, which do not have enough energy to spend on idle listening for network joining or to maintain synchronization with the network. Linked to this, we considered the hypothesis that a contention based communication scheme can better address the requirements of the I/O devices with strict energy budget. We validated this hypothesis by proposing an asynchronous communication scheme for the I/O devices. The precondition to realize this scheme was to have resourceful routers in the network to take the extra burden from the I/O devices. We conclude that the proposed scheme allows the I/O devices with strict energy budget to publish their data whenever they gather sufficient energy. This scheme makes industrial networks suitable for I/O devices with strict energy budget by completely removing the network management burden from these devices.

6.3 Future research directions

This thesis has addressed problems related to communication reliability and energy efficiency aspects in the industrial networks with resource constraint I/O devices. However, there are still open areas to be addressed in future work.

6.3.1 Adaptive channel hopping for industrial applications

Channel hopping techniques are proven to be able to improve communication reliability in an industrial environment by mitigating external interference and multipath fading. In this thesis, we considered the adaptive channel hopping for monitoring and control applications requiring low communication latency in a star/tree network topology. Later, blind channel hopping is considered for the industrial applications having low energy budget with relatively loose timing requirements in a mesh topology. There is a trade-off between using blind channel hopping and adaptive channel hopping. In the former case, an I/O device may switch to a bad one, which does not help to mitigate the interference and just wastes energy [89, 90]. However in adaptive channel hopping, I/O devices only change channels when interference is detected. Using adaptive channel hopping instead of considering blind channel hopping can be helpful. However, I/O devices need to scan all the channels continuously to be able to select a better channel to switch on, which can introduce a sig-
significant overhead. Although few works have been conducted by proposing adaptive channel hopping mechanisms for industrial applications [53, 91], it will be interesting to design an energy efficient adaptive channel hopping scheme in the future that can be used in the industrial networks having resource constraint devices.

6.3.2 Connection handover to address mobility

One of the novel features of DECT standard is its ability to switch parent (router) without losing the connection. This scheme can address the network mobility while improving the communication reliability. Similar technique is also adapted by the recently developed IEEE802.11ac standard. Although the hierarchical network management schemes proposed in this thesis can handle the network dynamics using different techniques such as resource delegation and over provisioning, it will be interesting to implement connection handover mechanisms in the industrial networks where the I/O devices can choose different routers while moving in the network.

6.3.3 Power control mechanism

In the hierarchical distributed network management scheme proposed in this thesis, the routers collect two-hop neighborhood information to choose a free channel offset without conflict. However, this process may not guarantee a collision free selection as the interference range is usually much greater than the transmission range. Such collisions in a scheduled communication system can be detected by monitoring the packet reception rates on each cell. The routers then use this information to decide on changing their channel offsets. As an alternative, routers can utilize distributed power control mechanism to adjust their transmission power level while detecting such interference.

6.3.4 Physical Layer improvement in IWSNs

Over the last decade, antenna diversity and multiple input multiple output (MIMO) techniques have been widely discussed to increase the reliability and throughput of various wireless systems. For instance, antenna diversity in DECT base stations is employed to combat multipath fading. Such technique can improve the communication reliability by achieving multiple different realizations of channel although it consumes higher energy. Such multiple antenna routers for industrial networks can be an interesting research domain. MIMO technique utilizes several antennas to transmit/receive a portion of a signal with spatial diversity that increases the system throughput without increasing the bandwidth. Orthogonal frequency division multiplexing (OFDM) takes this to the next step by using orthogonal sub-carriers in a
6.3 Future research directions

frequency band. While increasing the system throughput, OFDM also facilitate mul-
tilevel modulation schemes based on the channel state information. Such techniques
have been applied in the recently developed IEEE 802.11n, ac standard to increase
WiFi throughput to a next level. However, further research is necessary before these
technologies can be applied in low-power industrial applications [92].

6.3.5 Internet of Things

While the focus of this thesis is to enable reliable and energy efficient communica-
tion in the plant field, proper integration of the industrial network with the external
world is necessary to design the factories of the future. Recent activities in Internet
Engineering Task Force (IETF) shows enormous interest in designing such systems
by connecting the industrial systems with internet. A working group named 6TiSCH
is formed with an objective to integrate IEEE802.15.4e (TSCH) standard with several
higher layer IETF protocols such as IPv6, RPL, 6LoWPAN in the network layer, UDP
in transport layer, CoAP in application layer, which are already in place to enable in-
ternet of things (IoT). As a part of the EIT Digital RICH (Reliable IP for Channel Hopping networks) project, we already have a test bed running 6TiSCH protocols. We
are currently working on the integration of the proposed asynchronous communication scheme and hierarchical network management approaches in IEEE802.15.4e.
The next step will be the performance evaluation of the RICH stack by enabling IPv6
over it.


[38] P. Zand, K. Das, E. Mathews, and P. J. M. Havinga, “A distributed management scheme for supporting energy-harvested i/o devices,” in *Proceedings of
the 19th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Barcelona, Spain, September 2014.


[50] Digital Enhanced Cordless Telecommunications (DECT), Common Interface (CI); Part 1-5, ETSI Std. v2.3.1, 2010.


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List of publications in which he participated in reversed chronological order.


less, Mobile and Multimedia Networks (WoWMoM 2014), Sydney, Australia, 16-19 June 2014.


While having enormous potentials, present-day industrial wireless standards are not designed to support resource constraint devices in the network. This thesis addresses the requirements of such devices by reducing the network management overheads of the existing technologies. The proposed schemes provide energy efficient and reliable wireless communication between the network devices. This thesis also provides a solution to support a new industrial application class called 'fit-and-forget system', in which sensor nodes are only powered by energy harvesters.