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NOVEL NETWORK ARCHITECTURES AND ALGORITHMS FOR REAL-TIME INDUSTRIAL WIRELESS NETWORKS

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Chapter 1

INTRODUCTION

The use of wireless technologies in real-time automation systems offers attractive benefits, but introduces a number of new technological challenges. Behing the success of wireless networks in automation there are several advantages such as cost reduction, easy placement and installation, easy extension and mobile device connectivity. Wireless systems are in great demand also thanks to their flexibility. Devices can be rapidly installed without the added cost and time required by the installation of cables. Wireless technology is even more advantageous if installations are temporary. Wireless networks provide noticeable advantages in terms of mobility and costs reduction and they are in great demand due to their flexibility.

The proper functioning of wireless infrastructures is of vital importance for the acceptance and the success of the whole automation system. In addition to its main function of supporting data exchange, the network has to provide suitable traffic management for efficiently dealing with the typical requirements of automation systems.

One of the main challenges of wireless networks in automation is to provide a flexible architecture for the Quality of Service (QoS) management and for the support of real- time traffic. The QoS ability refers to the capability for providing different applications, users, or data flows, with different priorities, or to guarantee a certain level of performance to a data flow. This is done by traffic differentiation, i.e., assigning different priority levels to traffic flows and adopting suitable mechanisms to deal with different traffic priorities in a different way. In real-time applications, for instance, the main issue is to provide QoS by achieving predictability on the packet delivery times. Predictability is usually achieved by reserving resources and employing admission control under a priori assumed workloads, real-time constraints and failure conditions. The QoS mechanism can be influenced by many factors, such as node movement, node removal or addition, system updates or reconfiguration (due to network topology changes), routing, etc. Consequently, QoS management involves dynamic resource reallocation to cope with real-time constraints, in order to maximize the system benefit.

To provide control and monitoring of automation systems, hybrid networks can be employed, where the wireless infrastructure is connected to existing traditional wired backbones so that the information flow from the field device to the control room (and vice versa) is ensured. Hence, a cooperating group of both wireless and wired subsystems will be fulfilling their control tasks beyond physical layer borders. All of that will be carried out without compromising the real-time behaviour of the whole system. Therefore, based on the targeted application class, upper boundaries of the execution times will be determined and then real-time guarantees will be provided.

Many manufacturers in the discrete automation industry are investigating the feasibility of deploying wireless technology in order to improve process performance and/or optimize their asset utilization or combined with traditional wired connections.

Over the past few years, intensive wireless networks developments have been done for industrial cases.

Wireless technology is even more advantageous if installations are temporary. This is the case, for example, when machinery is being measured and tested for certification purposes priori to start-up or for maintenance, or again when it is necessary to modify wiring between control systems and the various devices operating in a plant. However, wireless networks will not totally replace wired networks, but will seamlessly integrate with them. In large factories, multiple wireless cells are deployed to efficiently implement automation cells to be interconnected by a real-time wired backbone.

A large number of process control network hardware manufacturers offer proprietary or standard wireless systems, instead of, or in combination with, wired systems. If we neglect proprietary solutions, which can be used in a limited number of contexts, and recent standards such as WirelessHART, which are slowly entering the market, due to the limited number of available chipsets and manufacturers, currently the most interesting solutions, thanks to their wide availability and acceptance, are those based on COTS standard communication protocols such as Bluetooth, IEEE 802.11, IEEE 802.15.4.

Among all the problems that should be faced to effectively use wireless in automation environment, this PhD thesis focuses on the integration of IEEE 802.11, Bluetooth and IEEE 802.15.4 on the factory floor. This integration seems to be very promising to cover a large spectrum of applications and to boost the use of wireless technologies in automation. However, each of these technologies has some limitations. Some of them will be discussed in next sections and innovative mechanisms to overcome these limitations and improve performance will be proposed. The experience gained during the PhD work and reflected in this thesis contributed to the ^{flex}WARE project, an EU project funded under the 7th FP (Seventh Framework Programme). The aim of the $^{\text{flex}}$WARE project is the integration of different technologies on the factory floor, to implement a flexible real-time wireless industrial network based on a two-tiered hybrid wired/wireless infrastructure.

The rest of the thesis is organized as follows. In Chapter 2 the requirements of a typical industrial network are discussed along with a two-tiered architecture that integrates a wired backbone with multiple wireless cells. The wireless tier connects the nodes that operate in each industrial automation cells.

In Chapter 3 the IEEE 802.11 protocol is presented. The CSMA/CA protocol adopted by the IEEE 802.11 standard cannot guarantee known delay times when several nodes compete for the channel. An innovative approach is therefore discussed to solve the problem of the increased number of collisions with increasing workloads that, in the standard protocol, cause bandwidth waste and abrupt throughput degradation.

In Chapter 4 a two-tiered IEEE 802.15.4 wireless architecture is presented. The advantages of the proposed architecture are discussed. The proposed architecture makes it possible to use the wired real-time network for highly-critical tasks that could not be supported over an unreliable medium, while the wireless network is used to cut the costs and increase the flexibility of the industrial network.

Chapter 5 shows a case study based on Bluetooth. One aspect investigated is how to enhance the support provided by BT to discrete manufacturing traffic through a novel transmission scheduling algorithm. Moreover, a novel frequency hopping management mechanism for Bluetooth networks used in industrial environments is proposed, which reduces the interference among co-located piconets, thus improving the network performance in terms of transmission delay and throughput.

Finally, Conclusions in Chapter 6 summarize the thesis.

Chapter 2

SYSTEM MODEL

2.1. Introduction

The main aim of the industrial architecture is to meet the requirements of typical factory automation applications. Such requirements drove the design of the network architecture and are summarized in the following section.

Additionally, in order for the proposed wireless solutions (presented in chapters 3-4-5) to be deployed in industries, different aspects will be considered to make sure that different industrial applications can perform their respective tasks in an effective manner.

Finally, a system architecture is shown which will fulfil the typically requirements coming from the preceding chapter.

2.2. Several Industrial System requirements

Predictability & simulation of system performances:

Predictability and guarantee of performances are key differentiating values of industrial scenario. The industrial system shall provide tools allowing the End User to simulate its network environment and determine in advance end-to-end performances of the system (across multiples cells and wired and wireless sections): end-to-end latency (min, max, average), jitter, throughput.

High availability of the connection with guaranteed performance: Industrial wireless systems operate in harsh environment and must adjust to potential interferences and high variation of the radio signal strength. Resistance to interferences is one of the main requirements. The design network must ensure high availability of the connection and predictability of performances. It shall provide a clear description of mechanisms put in place to adjust to interferers and changing conditions and consequences on latency and throughput.

Quality of Service provisioning: The network system shall implement advanced QoS mechanisms and a clear policy to insure guaranteed performances for predefined processes for both wired and wireless communication. Also QoS will be insured in the following conditions:

- increase of the number of stations connected
- occurrence of sporadic traffic (firmware upgrade, Internet traffic…)

The system shall provide high degree of QoS to all kind of operations (wired or wireless) involved in the system.

The network should cover a large area: factories in tipically scenario could have typical measures of: 500x500x6m, 1floor, indoor .The network should be able to operate in a harsh dynamic environment with large metallic parts (machines) and should consider factors like high temperature, dust, vibrations, humidity, metallic surroundings, etc. The area to cover includes a lot of large metallic parts (magazines).

High density of nodes and APs on factory floor and High number of nodes: To really reap the benefits of having wireless technology at its helm, the project should target those applications which offer a large number of nodes. The density of nodes should be high.

The timing requirements between the issuing of command and the execution should be met: should meet the timing requirements of its applications . In particular, the system shall target those applications which have strict timing requirements, between issuing and execution of the command.

The trajectory of nodes should have as little restrictions as possible: The movement of the nodes can be cyclic, on rail or free (along predefined paths). The design system should allow all these possible trajectories, which can be required by the applications.

Real-time communication guarantees for mobile nodes: During movement the nodes need to communicate in real-time. The requirement on real-time parameters like latency, jitter and roaming time depends on the application.

High reliability of the communication: The network system shall provide high reliability of the communication services. The message error rate shall be kept acceptable for the automation-application. This should be ensured both for wireless and wired communication.

Fault tolerance: The project shall prevent performance degradation in case of fault to any part of the system. It is mandatory to conduct a fault analysis of the system in order to provide fault tolerance mechanisms, The system shall be self healing: a communication system like the project is self healing, if the system detects communication errors and heals these errors by its own means. The mechanism to support this self-healing behaviour, which shall be configurable, and it shall be disabled particularly within safety-related systems.

The system shall enable device interoperability: Devices from different manufacturers shall interoperate with each other within architecture.

The system shall enable component interchange ability: It shall be possible to replace a component from one manufacturer by an equivalent device from other manufacturer.

The system shall support multiple wireless cells: Due to the large size of the area to be covered, multiple wireless coordination point will be required to provide coverage.

Allocation of resources should be provided for the communication between coordinator node and end-nodes: To grant several capabilities of the system such as bandwith, reaction time etc , it should provide a mechanism to allow a node the allocation of needed resources.

Clock synchronization for establishing a system-wide notion of time.

Communication between mobile nodes: The network system shall provide means for communication between nodes.

System Resource Scalability: Dynamic adjustment/increase in the resources of the system should be possible in order to meet the needs of nodes to ensure QoS.

Real time and Redundancy: Real-time in architecture must be omni-present, all devices must support real-time, although capability for real-time communication is not mandatory at every device. Moreover, the devices should be able to support redundancy functions.

Reducing non-determinism in wireless communication: the system should reduce the sources of non-determinism as much as possible on the wireless channel and/or on the wired medium.

The system shall enable to obtain typical upper bounds on the delivery times for application data over the network: Delivery time is the time needed to convey a service data unit (SDU, message payload) from a source node to a destination node, measured at the application layer interface. The system has to make it possible to obtain typical upper bounds on the delivery time for application data over the network in the non-faulty case. The delivery time can thus be estimated as the sum of the upper bounds of all the time components that make up the e2e data delivery time, i.e., transmission time, switching time (i.e. time overheads introduced by crossing the switching elements along the e2e path), middleware components processing times, hand-off time and so on.

The system shall enforce bounded and minimised delay jitter: it shall provide mechanisms to guarantee (at least statistically) given time bounds on all the components which may introduce delay jitter, while minimising delay jitter as much as possible. This minimisation is especially important for periodic control communications: Probabilistic communication (with high probability of delivery) across multiple wireless cells: the system aims at reducing as much as possible non-determinism in real-time communication in the network.

Real-Time traffic classes: the system shall handle the traffic according to the relevant real-time requirements. Four types of traffic will be defined:

- Periodic Real-Time: it has regular arrival times and features real-time constraints;
- Sporadic Real-Time: arrival times are not regular, but it is possible to determine a minimum interarrival time between two consecutive sporadic requests. This traffic features real-time constraints;
- Aperiodic Real-Time: it has irregular and unpredictable arrival times (it can even be one-shot). This traffic features real-time constraints;

- Non-Real-Time: this kind of traffic may exibit various arrival patterns and does not impose any real-time constraint. It only requires best effort service.

Mechanism to support dynamic environment: The working conditions in industrial environment are not static. They are changing, because of interference from working electric machines or moving metal objects. The system shall support working in such environments.

2.3. System Architecture

A large number of process control network hardware manufacturers offer proprietary or standard wireless systems, instead of or in combination with wired systems. If we neglect proprietary solutions, which can be used in a limited number of contexts, the most interesting solutions are those based on standard communication protocols.

Typically communication systems for industrial application automation have evolved from purely dedicated field-buses to Ethernet [1] based technologies. These Ethernet based technologies have their origins in the office environment and tanks to its success inside offices; they have been adopted at the factory floor level after minor modifications. As wireless networking has been widely adopted in offices, the use of wireless communication for industrial network increasing use is being made of wireless communication devices instead of, or combined with, traditional wired connections.

Large factories may include a very large number of nodes and high node density. Moreover, while such networks should cover a large area, the radio coverage of typically wireless technologies are quite small.

The approach, inspired on ^{flex}WARE project [2], sets up a industrial networked, which is based on wireless technology. In particular, sensor and actuator nodes are enabled to co-operate with other wired or wireless nodes in the system. This is especially needed for tomorrow's large factories, where production lines are set up in a way that the path of goods through production machinery is not statically predefined.

As a result, multiple wireless cells are required to provide coverage and the system shall support the interconnection of multiple wireless cells. For this reason and to satisfy the typical industrial requirements (described in the previous section) this work proposes a hierarchical system architecture made up of several independent automation cells grouped in Wireless Automation Cell (WACs). Each WAC is managed by a single controller, which is also connected to a real-time backbone. Based on the above discussion, the need for central management of the wireless infrastructure has been highlighted. Centralization can prove to be successful approach not only to provide mechanism to ensure QoS and real-time requirements.

Usually a central controller can be deployed control parts (or the entire) of the network by keeping track of the current view of the network and adjusts the configuration if needed.

As shown in Fig. 2.1, the system is composed of three different components i.e., Automation Devices, Controller Node and Coordinator.

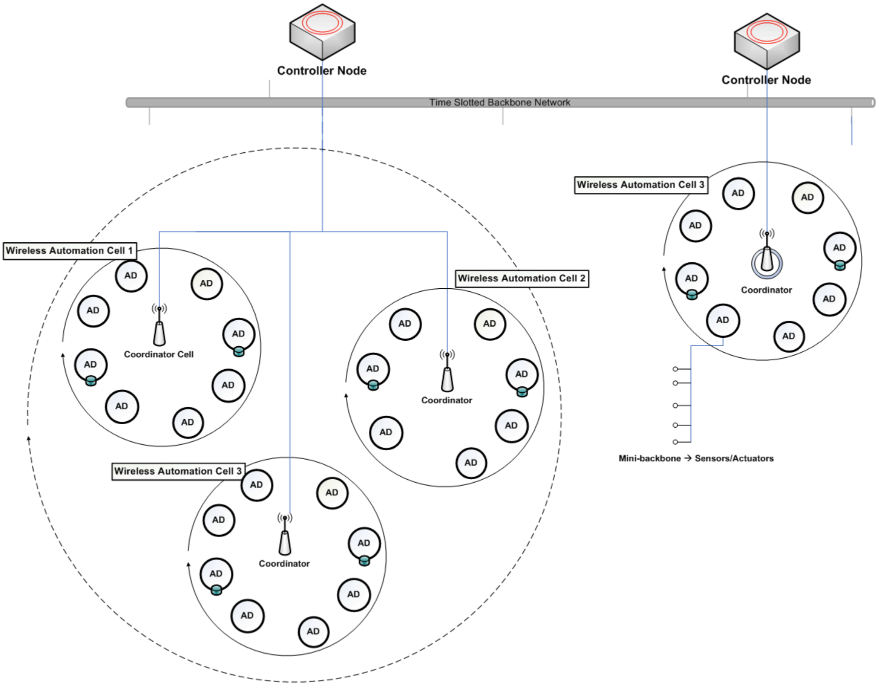

Figure 2.1: The proposed two-tiered architecture

The Automation Device (AD) provides a communication interface to field level devices. An Automation Device can also be a mobile node that moves inside a wireless cell. The

Coordinator nodes manage wireless automation cells and they are involved in the management of data transmission of the associated nodes.

The Controller Node is the central entity coordinating all the Coordinator of a given WAC in the wireless sub-system in order to provide the industrial application with the desired real-time behaviour and reliability.

More details about the functionalities implemented in the shown components are discussed separately in the following chapters for some main wireless protocols used in factory automation.

2.4. Conclusions

Bluetooth [3] [4] [5], IEEE 802.11 [6], IEEE 802.15.4 [7] [8] and the recent WirelessHART standard [9] are currently the main wireless standard protocols for industrial communication.

The integration of IEEE 802.11 [6], Bluetooth [3] [4] [5] and IEEE 802.15.4 [7] [8] on the factory floor seems to be very promising to cover a large spectrum of applications and to promote the migration from wired to wireless technologies. However, each of these technologies has some limitations.

They differ for the PHY and MAC layers, providing different transmission speeds and medium access control policies.

In the IEEE 802.11 family [4], nodes compete for the medium access according to the Carrier Sense Multiple

Access with Collision Avoidance (CSMA/CA) protocol. However, contention-based approaches are not able to guarantee an upper bound on the medium access delay, so they are not adequate for time-constrained traffic. For this reason, other approaches able to provide contention-free access have been developed.

IEEE 802.15.4 [7] [8] provides time slotting and two different operating modes, i.e., the beacon-enabled and the non-beacon enabled one. The beacon-enabled mode supports both a contention-free and a contention-based phase.

WirelessHART [9] adopts the IEEE 802.15.4-2006 [8] at the Physical layer and, on top of that, defines its own MAC layer. Time Division Multiple Access (TDMA) and channel hopping are used to control the medium access. This technique provides collision-free, deterministic communication between two devices [6].

The Bluetooth (BT) [3] [4] [5] technology uses a Master/Slave protocol with a maximum of 7 active slaves for each wireless cell, called a piconet, and adopts a combination of frequency hopping and time division multiplexing (FH-TDM). BT provides several features, which make it very suitable for several automation applications. The medium access is coordinated by a master, similarly to what happens in many wired fieldbus networks.

In the following chapters some solutions of BT, 802.11 and 802.15.4 are presented. The innovative approaches shown in the next sections are related to meet some requirements previously described, using the two tiered industrial network previously described.

Chapter 3

IEEE 802.11 CASE STUDY

3.1 Introduction

One of the main problems concerning the use of wireless networks in a industrial plant using the IEEE 802.11 protocol [6] is due to the unpredictability of both the wireless medium and the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol used at the MAC layer. Additionally the many obstacles, metal surfaces and block or reflects electromagnetic waves strongly limit the communication range [10] and increase the interferences and the packets loss probability. As a result the number of collisions significantly increases with increasing workloads, thus causing bandwidth waste and abrupt throughput degradation.

In literature [11] [12] some admission control, that decides about the acceptance of flows on the basis of the bandwidth currently used by the nodes already associated to the Access Point (AP), are presented to improve the global network performances. But it is not sufficient for the achievement of satisfactory Quality of Service (QoS). It is necessary to introduce a mechanism that is able to compensate dynamically for fluctuations in the wireless link characteristics as well as the load of mobile nodes that join and leave the AP.

The standard WLANs behaviour cause all active mobile stations to connect to a small subset of the APs and saturate their capacity, while other APs may still be under loaded. To improve this aspect several works [13], [14], [15], [16], [17] propose the use of load balancing techniques to improve the network performance, to the best of our knowledge none of them addresses the case for industrial WLANs, which not only comprise moving nodes such as robots that unbalance the load, but also are deployed in harsh environments characterized by fluctuating channel conditions.

The main tasks of a MAC layer for wireless industrial networks are channel access control and QoS. Since the wireless channel is random and time varying, the classical deterministic performance measures, e.g., the worst-case transmission times, should be replaced by probabilistic measures. The features [18] of the wireless channel that negatively impact on real-time performance are listed below.

- Physical Layer Overhead: to let the receiver of a packet acquire carrier/bit synchronization despite a noisy channel, most wireless systems use preamble.

- Channel Errors: a wireless transmitter propagates waveforms into multiple spatial directions at the same time. These waveforms can be subject to reflection, diffraction, or scattering [19].
- Path loss: the signal strength of a radio signal decreases with the distance between transmitter and receiver.
- Half-duplex operation of transceivers: wireless transceivers are not able to transmit and receive simultaneously on the same channel, because their own signals would drown all signals from any other stations.

These aspects are particularly important in factory automation systems, where response times are considered much more significant than other performance metrics.

Another aspect is the mobility of users, which may cause the end-to-end path to be variable. In the case of roaming, a mobile node should obtain the same QoS in the destination AP as that obtained in the source AP. IEEE 802.11 [6] networks are based on the Distributed Coordination Function (DCF), which is a best-effort method and does not support QoS for time-critical applications. All stations in a Basic Service Set (BSS) have the same priority to access the channel.

To improve the classical mechanism the 2007 revision of IEEE 802.11 [6] introduced the EDCA protocol. Using EDCA protocol it possible to obtain some probabilistic differentiation mechanisms to guarantee bandwidth, packet delay or jitter for soft real-time flows.

3.2. State of Art

In literature are shown the possibility of managing QoS using three different approaches [20]:

- **Service differentiation:** It use a priority scheme, an example is described in [21].
- **Admission control and bandwidth reservation**: the most diffused approach. This approach advances the service differentiation, that does not deal well with high traffic load conditions and does not introduce any rules to guarantee flow schedulability, but it has several problems. The management of mobile nodes, as the network should provide the same QoS levels across different APs, but the wireless channels unpredictability does not offer a mechanism to control the channel state and the packet loss values.
- **Link adaptation and load balancing**: the third technique is the use of link adaptation [20] and load balancing algorithms [23]. For example the authors in [24] shows a load balancing mechanism that manages the number of users per AP statically, as it divides the number of

users by the number of APs. Another literature work [25] proposed an algorithm that finds the Most Congested Access Point (MCAP) to decrease congestion and balance user traffic in IEEE 802.11. While a Cell Breathing Technique to balance the AP load and improve the QoS of real-time applications is presented in [26]. The proposed technique reduces the radio range of the congested APs and the number of users per congested AP.

3.2.1. A load balancing mechanism

The IEEE 802.11 standard [6] does not specify any automatic load distribution mechanism. In a wireless network with many distributed APs, a mobile station always selects the AP with the highest signal to noise ratio (SNR). The mobile nodes sense nearby APs without any attention to the real workload of the AP selected. In several cases the load on the APs is not balanced and one AP may have to manage many more mobile nodes than another neighbouring AP. An unbalanced load causes performance degradation in the system.

There are several different approaches for load balancing in current literature. An innovative approach is shown in [23], which is a load-balancing mechanism for IEEE 802.11 networks that is completely transparent for mobile stations.

The authors implemented a distributed database system (DS), directly connected to the APs through the wired channel. Through a new protocol the APs exchange information such as the current network load, the number of active mobile stations and so on. The described load balancing approach [23] improves the general system performance. However, balancing the workload is not always the best choice, as there can be nodes with lower signal quality and/or nodes with less strict timing constraints than others.

My thesis shows a new mechanism that uses the APs' utilization and Deadline Miss Ratio (DMR). Research carried out in the field of adaptive resource management for industrial wireless networks is very limited.

The start points of the new proposed approach are summarising in the following.

- This channel access mechanism is unpredictable, as it does not avoid collisions. The wireless link characteristics are not constant and vary over time and place [27].
- So described in the system requirements analysis wireless industrial networks are exposed to potential interferences and high variations in the radio signal strength because they operate in harsh environments with large metallic parts (machines) and should consider factors like high temperature,

dust, vibrations, humidity, metallic surroundings, etc.

- An admission control algorithm is not sufficient to guarantee acceptable performance. To handle the large number of retransmissions required to maintain an acceptable level of reliability, the 802.11 network can experience too high deadline miss values, because link capacity is limited. To improve the standard protocol it is useful to balance the load of both real-time and non real-time flows over different APs. The technique here proposed is based on the previous approach described in [6], but it provides significant advances on existing literature as it takes into account both the requirements of RT traffic and previous conditions to dynamically adapt the load of APs even in the presence of mobile nodes and highly fluctuating wireless links

3.3. System Model and Proposed Approach

It is assumed that the evaluated system has the same two-tiered architecture shown in the Chapter 2. It consists of a collection of Wireless Industrial Automation Cells (WIAC) connected by a wired backbone, as shown in Figure 3.1. Each WIAC contains an Access Point and multiple wireless nodes. The controller node, directly connected to the backbone, has a global view of the network and thus is able to perform corrective actions whenever an AP experiences performance degradation. This architecture enables centralized control of the APs at the controller node and data exchange between WIACs via the wired real-time network.

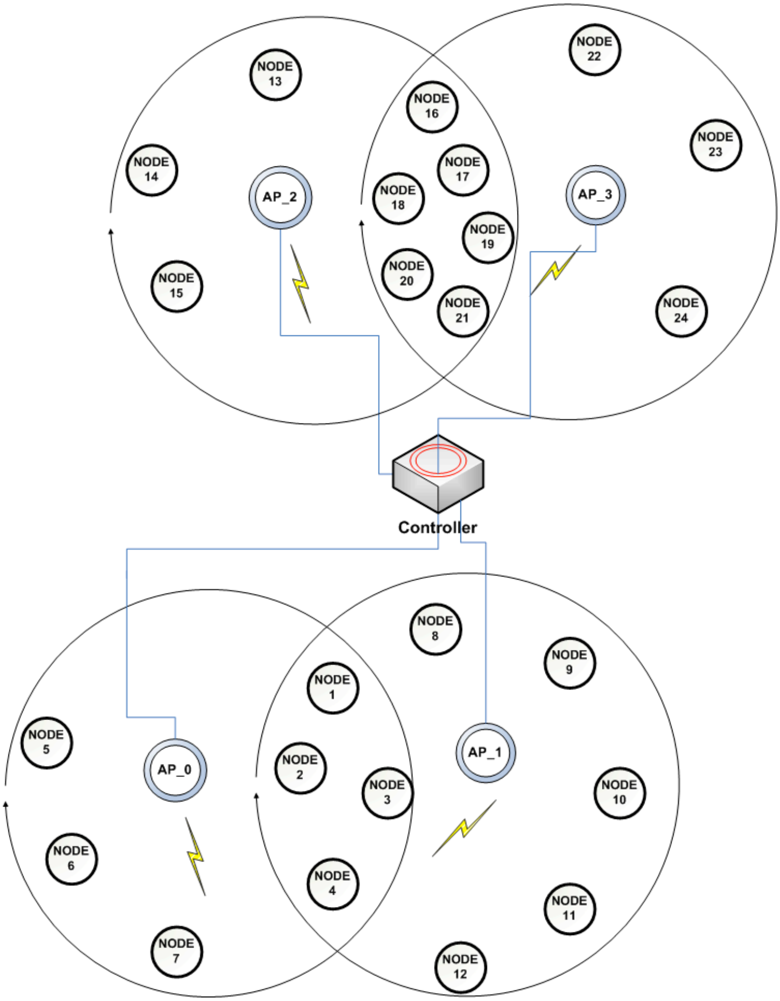

Figure 3.1: Network Architecture

Nodes can be either mobile or non-mobile and can be covered by either one or multiple APs. The proposed approach manages mobile nodes and nodes inside the overlapping zone, i.e. nodes covered by multiple APs. If the Deadline Miss Ratio (DMR), measured by an AP is greater than a given value (set by application) the proposed approach, here called dynamic load balancing (DLB) algorithm, checks whether the network is balanced. If the network is unbalanced the DLB algorithm makes a node de-associate from its AP and join a better AP.

The balancing algorithm calculates a target utilization factor for each AP, to improve the real-time performance (in terms of DMR and packet loss ratio). The target utilization is the maximum utilization of the wireless channel under which the real-time performances of the relevant AP are acceptable.

The ratio between the currently measured utilization and the target utilization of the APs is balanced across the network by moving nodes from an AP to another in the same overlapping zone.

The DLB algorithm finds out the stations that determines the performance degradation based on the bandwidth utilization and chooses the best AP to re-associate the mobile stations.

The load-balancing algorithm is triggered by the following events:

- performance degradation of the wireless channel,

- the arrival and/or the mobility of new or existing stations.

The controller stores information about current network parameters in its own internal structures. Some information, needed to general network, are exchanged between WLAN entities and wired network connecting the APs and the controller.

The controller stores the following parameters:

- $\alpha_i(k)$ is a parameter used by the balancing algorithm in order to determine whether the load is balanced or not. The α parameter is dynamic, as it varies as a function of the deadline miss ratio (DMR) measured at time k - 1. The values of the parameter α are shown in Table I.
- $U_i(k)$ is the utilization of the i^{th} Access Point obtained in the k^{th} observation window. This is calculated as the sum of the workload introduced by all nodes divided by the bandwidth of the wireless link.
- $U_i^*(k)$ is the target utilization for the i^{th} Access Point. It is a desired value determined a run-time, which is used to take into account fluctuations in the wireless channel. The system periodically re-computes the target utilization factor on the basis of the DMR experienced by each AP during the previous observation window. This

calculation follows the rules described in the third column of Table I. The system decreases the target utilization value using a multiplicative factor when the DMR is high, while it increases the target utilization value by an additive factor when the DMR is low. As a result, the target utilization factor of APs is dynamic and depends on the conditions of the wireless link.

- $U_{rel,i}(k)=U_i(k)/U_i^*(k)$, is the ratio between the utilization factor measured at the k^{th} observation window and the relevant target utilization factor. This parameter is used by the AP to determine which nodes have to be de-associated from their AP and re-associated with another one. In a following step the algorithm identifies the zones from which and to which the nodes are to be moved.
- $\overline{APU}$ (Access Points' Utilization) is the mean value of the utilization in the various APs, calculated by dividing the sum of the U_i of every AP by the number of APs.

The network is said to be in a balanced status if, when U_i is the utilization band of the i-th AP, the following relation holds:

$$\delta_1 \leq U_i \leq \delta_2 \qquad (1)$$

Where δ_1 is defined as $\overline{APU}$ - $\overline{APU}$ *α and δ_2 is defined as $\overline{APU}$ + $\overline{APU}$ *α.

If the experienced DMR (measured a run time) value increases, the α value will decrease and so also the width of the $[\delta_1; \delta_2]$ interval. If that event occurs the chance of finding an overloaded AP increases. Smaller values of α allow a faster execution of the balancing algorithm despite a lack of precision in the balancing process. Greater values of α make the new computed load more balanced but the algorithm execution time grows.

TABLE I

RULES TO DETERMINE THE α_i AND U_i* PARAMETERS

	α_i (k)	U_i*(k)
DMR_i (k-1) < 1%	25%	0.01 + U_i*(k-1)
1% < DMR_i (k-1) < 3%	20%	0.95 × U_i*(k-1)
3% < DMR_i (k-1) < 5%	15%	0.90 × U_i*(k-1)
5% < DMR_i (k-1) < 7%	10%	0.80 × U_i*(k-1)
7% < DMR_i (k-1) < 10%	5%	0.70 × U_i*(k-1)

The main cycle of the load-balancing algorithm can be summarized in the following steps:

1. Compute the average network utilization
2. Compute the value of α
3. Identify the overloaded APs, i.e., those for which relation (1) does not hold.
4. For each overlapping zone *j*, compute the corresponding α_i as:

$$\beta_j = \frac{\left(\sum_i U_{rel,i}\right)^2}{n \cdot \sum_i U_{rel,i}^2} \qquad (2)$$

This is similar to what is done in [23], but we consider the target utilization factors instead of the mere throughput values.

5. Find the overlapping zone associated with the minimum α_i

6. Find the most heavily loaded and the least loaded APs among those overlapping in the zone associated with the minimum α_i.

7. Move the selected station from the most heavily loaded AP to the least loaded AP. The station to move is the one whose used bandwidth value is the nearest to the difference (load of the most heavily loaded AP).

The simulation of the algorithm described in [23] experiences some oscillations due the disconnecting process of a mobile station from one AP to another one, and then it re-joins to the original AP. This problem is typical in scenarios with very few nodes and in the presence of nodes using higher bandwidth than the other mobile stations. To avoid such a problem, the DLB algorithm stops after four iterations of its main loop. The algorithm aims is that to detect such fluctuations and remove them from the balancing output.

The interactions between three distributed entities, that cooperate to manage QoS (the (mobile) node, the Access Point and the Controller), are described in Figure 3.2. Whenever a node establishes a new connection with an AP, it sends a connection request message. This message contains the amount of bandwidth needed by traffic flows of the considered node.

Before to accept the new connection the AP checks whether the network utilization is still below the target utilization level despite the new station arrival, i.e. it checks whether the sum of the current utilization plus the utilization requested by the new station is smaller than Ui*(k). If this condition holds, the node is simply accepted. If, on the other hand, the condition does not hold, the AP sends a message to the Controller to ask for a new run of the load balancing algorithm, in order to find a better distribution. At this point, the Controller executes the load-balancing algorithm and, if it is able to successfully compute a new load distribution, it sends the information about the new node distribution to all the APs involved in the load redistribution, that is, the APs that have to attach or detach stations.

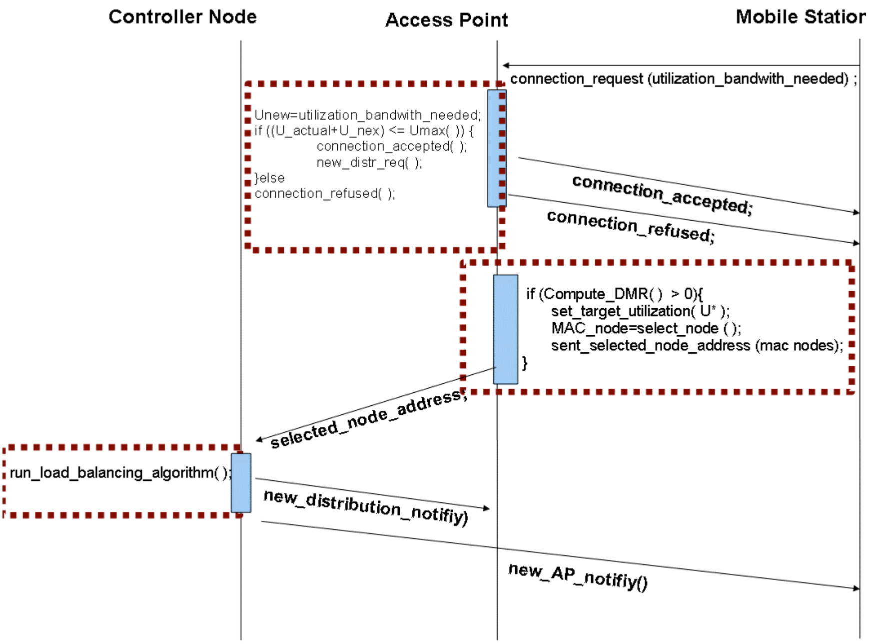

Figure 3.2: Sequence diagram of the proposed load balancing mechanism

The wireless channel is time varying, therefore it is possible that the target utilization value of APs vary even without any node joining or leaving them. For this reason it is convenient to run the load-balancing algorithm when the DMR of any AP exceeds a predefined threshold, it occurs whenever an unbalanced AP is found in the industrial network.

3.4. Performance Evaluation

In order to study the performance of LBD algorithm was simulated the two-tiered architecture addressed in the chapter 2 using ns-2 [28]. Some assumption are made:

- the activities are mainly periodic.
- real-time flows are sent by all wireless stations,
- the controller manages the load as described in the previous section.
- The mobile nodes communicate:
- among themselves to carry out the manufacturing activities.
- with their AP and with the Controller to exchange the information requested by LBD approach.
- The controller coordinates the activities of nodes.
- The messages are periodic real-time flows, characterized by regular arrival times.

To outline the benefits of the proposed load balancing algorithm (dynamic LBA), it are carried out two simulation campaigns:

- to compare the performance obtained using LBD to that obtained without any load balancing algorithm.
- to compare the performance obtained using LBD approach to that obtained with the classic load balancing algorithm (LBA) described in [23].

3.4.1. Scenario description

Using the same network topology for both measurement campaigns, four APs and one Controller, linked by a full duplex 100Mbps wired link.

Every mobile station sends packets to a mobile station connected to another Access Point:

- mobile stations attached to AP 0 have to send packets to re-ceivers attached to AP 3,
- mobile stations attached to AP 2 send packets to receivers attached to AP 1.

The scenario implements two overlapping zones:

- one between AP 0 and AP 1 (Zone 1),
- the other between AP 2 and AP 3 (Zone 2).

In the following tables some specification of simulated scenario are described.

TABLE II

SIMULATION PARAMETRS

Simulation Time	*120 seconds*
Relative Deadline Real-Time Flows	*0.05 seconds*
The traffic is constant bit rate. *Period=Relative Deadline*	*0.05 seconds*
Packet size	*64 bytes*

TABLE II

SIMULATION CHARACTERISTICS

✓ *Four simulations for each measurement campaign.*
✓ *The first simulation starts with 12 active stations and after the number at every new simulation was increased: 16 active stations for the second simu-lation, 20 active stations for the third and 24 active stations for the fourth.*

3.4.2. Dynamic LBA vs. no LBA

The evaluated QoS parameters are global:

- end-to-end delay (computed at Mac Layer between sender and receiver station)
- global Packet Loss Ratio (PLR).
- every AP load,
- the global throughput
- the global deadline miss ratio, The deadline miss ratio was computed as the number of packets which arrived after their relative deadline divided by the number of arrived packets.

The load distribution is shown in Figure 3.3. As can be seen, increasing the number of active stations the LBD approach makes the controller algorithm start balancing the network, rendering the load equally distributed among all the APs. This is because mobile stations in overlapped zones have been moved from one AP to another, as shown in Figure 3.3.

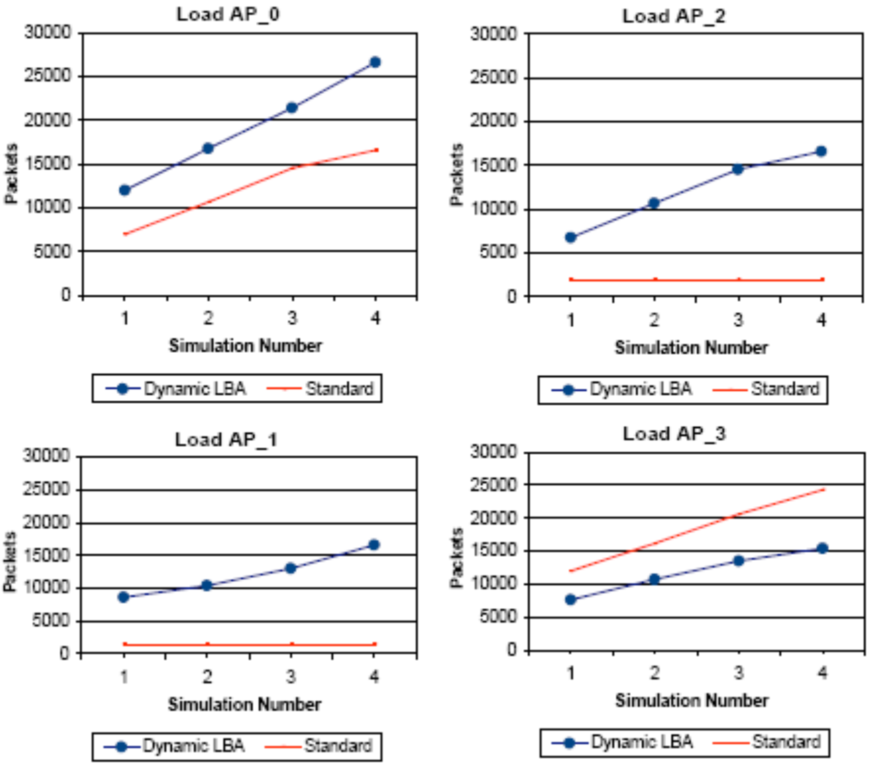

Figure 3.3: Load Distribution among APs

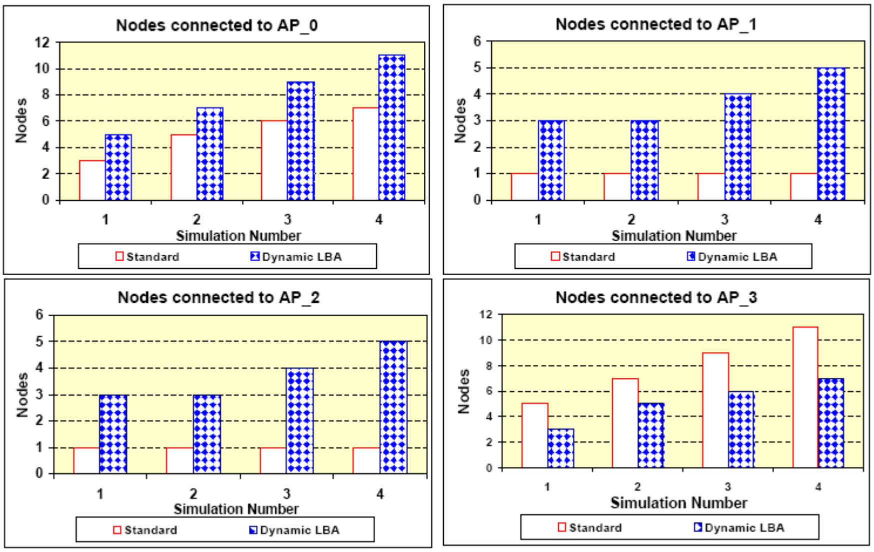

Figure 3.4: Mobile Nodes connected to each AP

The most important results (shown in figure 3.5) are those showing average end-to-end de-lay, packet loss rate, deadline miss ratio and throughput. The obtained throughput values are very high, this means that the wireless channel does not reach saturation, even if all available transmitters are active.

On the other hand, while packet loss rate and end-to-end delay rapidly increase if we activate more and more traffic flows in the non-controlled scenario (with 24 active stations, the average delay is about 0.09 seconds, while the PLR is about 14%), they grow very slowly in the controlled scenario (with 24 active stations, the average delay is about 0.028 seconds, while the PLR is about 7%). The results show that the controlling algorithm, while providing a mechanism to manage the network overload, also improves the support to real-time traffic (even if no guarantees can be given), as the deadline miss ratio is very low, even in the most heavily loaded scenario.

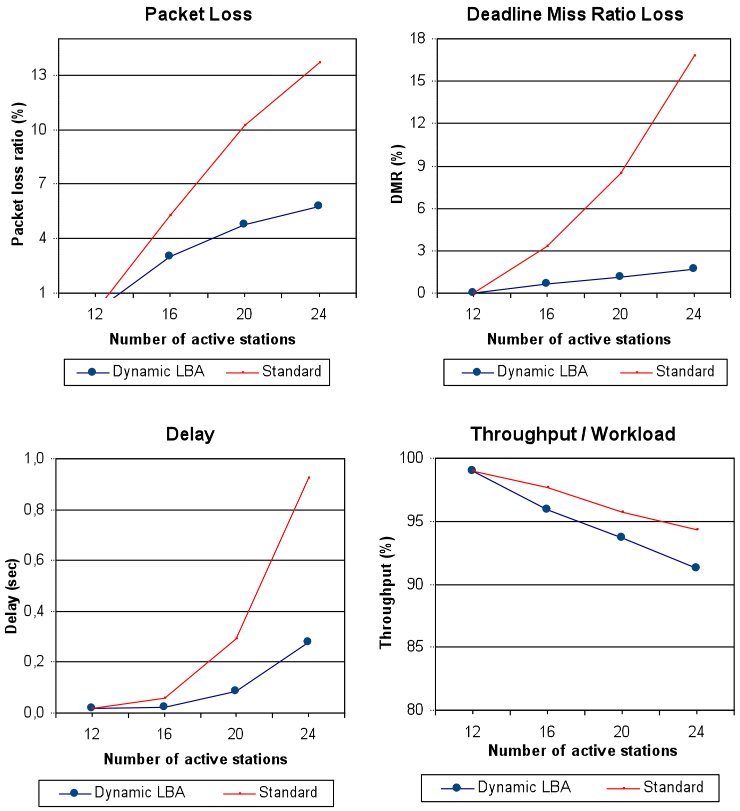

Figure 3.5: Measured QoS parameters

3.4.3. Classic LBA vs. Dynamic LBA comparison

In the previous scenarios all the APs and all the overlapping zones, in simplistic assumptions, feature the same

Packet Error Rate (PER). In this analyzed scenario the performance of the dynamic load balancing algorithm are similar to those of previously known approaches like [23]. In a industrial scenario different APs can experience a different level of electromagnetic interference due to the proximity of electromechanical machines, robots, etc. In the following another simulation campaign, using the same scenarios previously described, are shown, but setting a different PER for the different wireless links.

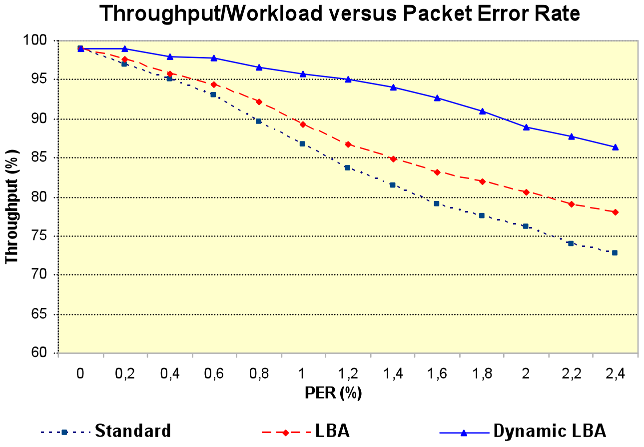

Figure 3.6: Throughput vs. PER

The results in Fig. 3.6 show:

- the throughput obtained using the DLB Algorithm decreases at a smaller rate than that obtained using both the standard association and the load balancing algorithm in [23];
- using the dynamic LBA the network suffers from a less serious performance degradation.

The reason for these results is that the packet error rate is mitigated by the adaptable target utilization of APs. In fact, the APs experiencing higher packet error rates decrease their target utilization value, so they serve a smaller number of nodes but provide them with a better QoS. We can conclude that the classical load balancing algorithms tend to achieve an equal number of nodes associated with each AP, in the proposed load balancing mechanism the better is the signal quality, the higher the number of nodes per AP. In this way the network performance are optimized.

3.5. Conclusions

WLANs based on the IEEE 802.11 protocol [6] is used in industrial network, however several mechanism should be implemented, to achieve satisfactory Quality of Service (QoS). It is due to the unpredictability of the wireless medium and the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol used at the MAC layer.

The novel load-balancing algorithm here described takes into account both the bandwidth utilization and the state of the wireless channel, so as to compensate dynamically for fluctuations in the wireless link characteristics as well as the load of mobile nodes that join and leave the AP.

Chapter 4

IEEE 802.15.4 CASE STUDY

4.1 Introduction

The IEEE 802.15.4 standard [7] [8] fits well the typical requirements of networked embedded systems found in many contexts, such as factory communication, home and building automation, wireless sensor networks. These environments feature applications in which small and simple embedded devices, such as sensors and actuators, spend most of the time in a “sleep” state and wake up either with a given periodicity (which is known a priori) or following the occurrence of an event. Typically, these applications do not require high data rates, but are time-critical, meaning that the timeliness property of the application is as much important as its function [29],[30],[31].

The IEEE 802.15.4 standard specification [7], [8], provides a limited support for real-time communication. The beacon-enabled operating mode (the most suitable one for real-time traffic management) implements a superframe structure consisting of a *Contention-Free Period* (CFP), which can be used for real-time transmissions, and of a *Contention Access Period* (CAP), which can be used for best-effort or non real-time traffic. However, the length of the CFP is limited to a maximum of seven Guaranteed Time Slots (GTS), which the PAN-Coordinator (PC) allocates to provide nodes featuring time-constrained traffic with a minimum service guarantee. On the other hand, the CAP, implements the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol. Collisions and the backoff mechanism make the network access time highly variable and unpredictable. As a result, it is difficult to support the traffic of a large factory plant using a plain IEEE 802.15.4 network. The low number of GTSs provided by the 802.15.4 standard represents significant limitations in large networks, so a mechanism to overcome such a limitation would be beneficial. Moreover, the real-time support provided by the GTSs could be improved making the GTSs allocation deadline-aware, i.e., granting a higher priority in receiving a GTS to nodes with more pressing deadlines, (instead of following a First Come – First Served (FCFS) rule).

The industrial environments feature applications in which small embedded devices, such as sensors and actuators, spend most of their time in a “sleep” state and wake up either with a given periodicity (which is known a priori) or following the occurrence of an event to be signalled. Typically, these applications do not require high data transfer rates, but are time-critical, meaning that the timeliness property of the application is as much important as its function. Nevertheless, several works in the literature investigated the use of IEEE 802.15.4 networks in industrial environments from different points of views, e.g., analysing link reliability and proposing algorithms to improve the support of either QoS or real-time constrains. However, while such works solve specific problems (or improve specific features) of the IEEE 802.15.4 protocol, this chapter at integrating some of the relevant techniques proposed so far in a complete architecture for factory communication, which is able to meet the typical requirements of industrial networks.

We hereby propose a two tiered architecture. The first tier is a field-level IEEE 802.15.4 network, which is organized in automation cells, each served by a PAN Coordinator and controlled by a special controller node. The second tier is a real-time wired backbone. This architecture facilitates the integration of wireless control into factories, which already own a wired industrial network. Moreover, it is possible to combine the advantages of both wired and wireless networks, as it is possible to use the wired real-time network for highly critical tasks which could not be implemented over an unreliable medium, while the wireless network can be used to cut the costs and increase the flexibility of the industrial network.

4.2 The proposed Architecture

To satisfy all the typical requirements, we propose a hierarchical system architecture made up of several independent automation cells, i.e., IEEE 802.15.4 PANs, grouped in Automation Clusters (ACs). Each AC is managed by a single controller, which is also connected to a real-time backbone. As shown in Fig. 4.1, the system is composed of three different components i.e., Automation Devices, PAN Coordinators and Cluster Controllers .

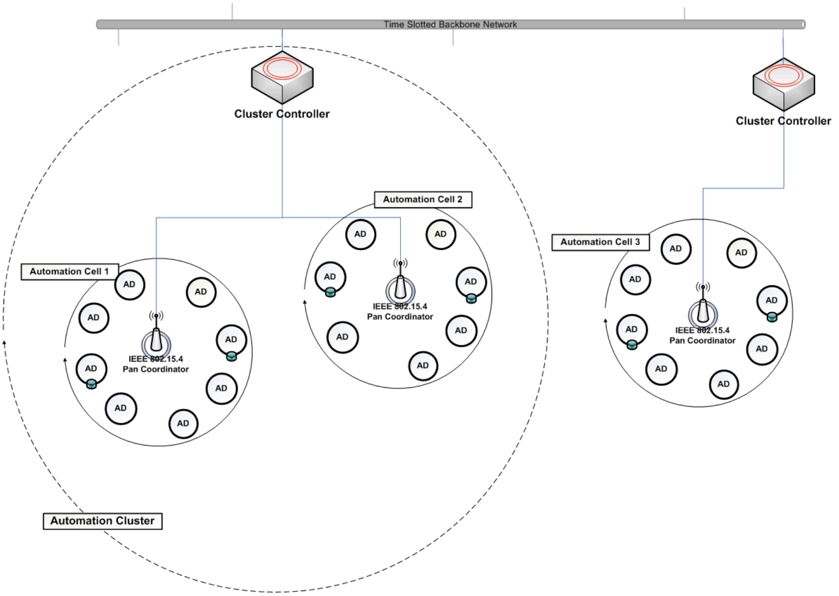

Figure 4.1: The two-tiered architecture

The Automation Device (AD) provides a communication interface to field level devices. It can be either an IEEE 802.15.4 end device or a coordinator in a clustered network (fig. 4.1). An Automation Device can also be a mobile node that moves inside an AC. In this case, it is likely that the device is also energy constrained.

The PAN Coordinators (PCs) are the heads of star or cluster-tree IEEE 802.15.4 PANs. They coordinate data transmission of the associated nodes and, in our architecture, they are in charge of scheduling traffic within their respective PANs, so that real-time guarantees are met and QoS is maintained.

The Cluster Controller (CC) is the central entity coordinating all the PAN coordinators of a given AC in the wireless sub-system in order to provide the industrial application with the desired real-time behaviour and reliability.

4.2.1 Cluster Controller node

The main functions of the CC node are represented in Fig. 4.2. It is in charge of:

- the management of a real-time communication between two node belonging to different cells,
- frequency management to limit interferences between adjacent cells,
- resource management to avoid collisions in case of overlapping PANs and to expedite the association to a different PAN coordinator of a mobile node.

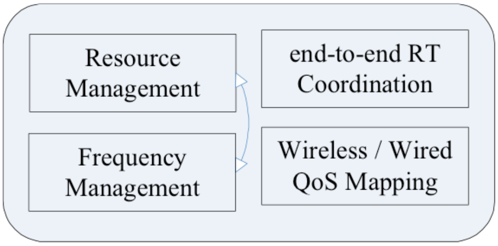

Figure 4.2: Cluster controller node architecture

The Resource Management module runs a load-balancing algorithm to split the traffic flows onto spatially overlapping PANs, so that some spare capacity is left in the cells for the support of traffic flows from mobile nodes.

In the case a real-time flow has to cross two different PANs, the end-to-end RT Coordination module cooperates with an Admission Control module which is located in the PC to assess the scheduling feasibility once the traffic flow will be introduced.

To prevent interferences between different PANs, each PAN should use a different radio channel. The Frequency Management module of the CC communicates to the PCs during the nodes' initialization which channel they should use for transmissions. Such a selection can be based on the node position, with a virtual grid subdividing the factory area into a number of small uniform regions, each one hosting a cell. As the characteristics of an industrial plant are known a priori and usually do not change, it is possible to use a static approach such as that proposed in [32], which is based on a fixed table and on the coordinates of nodes. Moreover, it is possible to use a technique to perform online channel assessment under cross-channel interference, such as the one presented in [33], and reassign the channels if the packet error rate does not meet the application requirements.

Finally the Wireless/Wired QoS Mapping module should do the mapping of QoS parameters between the backbone and the 802.15.4 network, according to the requirements of traffic flows.

4.2.2 PAN Coordinator node

The PC node architecture is shown in Fig. 4.3 An Admission Control module is needed to ensure that the addition of a new node or a new flow will not affect the performance of previously admitted traffic.

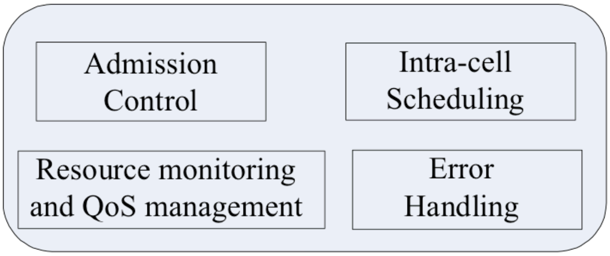

Figure 4.3. PAN Coordinator node architecture

The admission control assesses the acceptability of new flows, by interacting with the Resource Monitoring module.

Such a module keeps track of the used resource, analyzes the real throughput and the real performance in terms of deadline miss ratio and packets loss ratio. These information are used by the admission control algorithm to determine the acceptance of a new flow.

The Intra-Cell Scheduling module manages both the periodic and aperiodic real-time traffic. To address the real-time requirements, the IEEE 802.15.4 protocol provides for bandwidth reservation and collision avoidance thanks to the GTS mechanism. In this way it is possible to provide service guarantees in terms of throughput and delay. However, in the IEEE 802.15.4 protocol GTS are assigned statically and their number is limited to seven. This represents a significant limitation for large networks. A possible approach to these limitations is proposed in [34], where multiple nodes are allowed to share the same GTS time slot in different super-frames on the basis of their maximum allowed delays, and GTSs are scheduled according to the Earliest Due Date Algorithm. We are also investigating the use of the Earliest Deadline First [35] algorithm in an improved GTS scheduling mechanism combined with a server-based approach to schedule aperiodic flows.

Non real-time traffic is not scheduled as it uses the CAP featuring slotted CSMA/CA. Nevertheless different priority levels should be supported to achieve traffic prioritization. Actually, the IEEE 802.15.4 protocol does not support any prioritization mechanism. However, some work has been done in literature to add the support for different QoS classes in the IEEE 802.15.4 protocol. A service differentiation strategy to improve the performance of slotted CSMA/CA for time-critical events is presented in [36], where the parameters of slotted CSMA/CA are adequately tuned to handle the different priority of the messages. However, this strategy implements only two classes of priority, which may not be enough for complex industrial networks. For this reason, we are currently investigating on how to set the parameters of the slotted CSMA/CA algorithm in a way that it is possible to obtain several different priorities to implement several service classes.

To meet the reliability requirement, the Resource Monitoring and the Error Handling modules are defined. The former manages and shares the availability of resource, for example it periodically senses the channel and logs RSSI measurements to assess the quality of the channel. The latter operates in strict collaboration with the Intra-Cell Scheduling in such a way that, in case of transmission errors, the PC shall be able to adapt the schedule to guarantee the requirements of the traffic flows.

4.2.3 Automation Device

The architecture of the Automation Device is depicted in Fig 4.4.

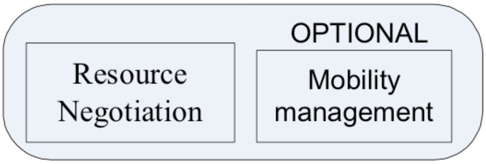

Figure 4.4. Automation device architecture

The Resource Negotiation module of the node communicates the requirements of its traffic to the PC for processing by the admission control module. If the node is mobile, it should be able to seamlessly reassociate with a different cell in a timely manner. This could be an issue for standard IEEE 802.15.4 networks, as the work [37] shows that IEEE 802.15.4 is not able to maintain node connectivity for fast moving nodes i.e., mobile nodes that change coordinator quickly. The moving nodes stop re-associating after a few seconds and this behaviour worsens at higher speeds and when multiple nodes are mobile. For this reason, we are investigating handoff mechanisms, where the reassociation of a node to a different cell is assisted by the CC, through which PCs can exchange in advance the information needed for the reassociation.

4.3 Conclusions

This work reports ongoing work on a two-tiered network architecture for factory communication, based on the IEEE 802.15.4 protocol. The work provided an overview of the main requirements of such architecture and discussed how to solve the main issues by exploiting recent research results on the 802.15.4/ZigBee protocol. This work is inspired by the architecture proposed in the ongoing Flexible Wireless Automation in Real-Time Environments ($^{\text{flex}}$WARE) IST FP7 project [2], but differs from the project mainstream as $^{\text{flex}}$WARE activity mostly focuses on the IEEE 802.11 protocol. Our current work is dealing with the simulation of the proposed architecture to assess the advantages and limitations of the IEEE 802.15.4 protocol from an experimental perspective.

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Chapter 5

BLUETOOTH - IEEE 802.15.1 CASE STUDY

5.1 Introduction

In chapter 2 are shown the typical architecture to satisfy several industrial requirements. So the IEE 802.15.1 - BT [3] [4] [5] scenario refers to the large factories, where multiple wireless cells are deployed to efficiently implement automation cells to be interconnected by a real-time wired backbone. Wireless networks will not totally replace wired networks, but will seamlessly integrate with them.

However, transmissions of co-located wireless cells within a plant may determine interference due to the broadcast nature of wireless transmissions. Frequency multiplexing can be exploited to allow parallel transmissions while avoiding collisions, as the use of several carriers with different frequencies provides independent transmission channels. The main problem lies in the definition of a suitable policy to avoid that independent channels will be using the same frequency at the same time. In the BT standard time is organized into time slots of a constant length (625 microseconds) based on a Time Division Multiple Access/Time Division Duplex (TDMA/TDD) scheme. Scheduling is handled by the Master, alternating a Master transmission with one by a designated Slave. This means that scheduling occurs in pairs of slots (i.e., the Master/Slave pair). BT implements a Frequency Hopping scheme, in which the Master establishes the sequence of transmission/reception frequencies, which will be known to all the piconet Slaves. They will calculate the hopping sequence autonomously, on the basis of the Master address and its clock. A slotted channel is particularly useful for process control applications because it simplifies clock synchronization in the various stations.

In addition, when combined with the M/S approach, it enables accurate definition of any delay in data transmission and thus makes deterministic scheduling possible. In process control, in fact, the need to guarantee timeliness in communications can be efficiently met by centralized management of access to the physical channel. Fieldbuses which adopt a centralized protocol (e.g. WorldFIP, Fieldbus Foundation, etc.) are particularly suitable for traffic with strict time constraints. However, as demonstrated in [38] and [39], a Master/Slave (M/S) approach in BT is sometimes inefficient in process control applications, which usually feature periodic data exchange with a known dynamic.

The aims of this chapter are:

- a new approach to real- time scheduling in BT networks, which advances the state of the art because it combines deadline-aware scheduling with the S/S operating mode and handles both periodic and aperiodic traffic in an integrated way.
- a new approach to cope with the interference between co-located piconets. According to the Bluetooth protocol, each piconet uses an independent frequency-hopping algorithm, which ranges among 79 channels. As no synchronization between different piconets is foreseen, two piconets might be transmitting on the same channel, thus generating collisions and message loss. In the following A frequency management approach, called a Piconet Management Approach, which avoids collisions through a suitable synchronization strategy, is described.

The chapter is organized as follows. Section 5.2 deals with the case for Bluetooth in industrial automation, while Sect. 5.3 addresses related literature and the motivation behind this work. Section 5.4 describes the Piconet Management Approach here proposed to reduce co-channel interference in industrial networks, presents a simulative assessment and discusses the results obtained with a varying number of co-located piconets. Section 5.5 presents an approach to transmission scheduling in BT networks that not only renders scheduling deadline-aware but also enables the integrated management of all real-time traffic, both periodic and aperiodic. Finally, Section 5.6 concludes the chapter and outlines some hints for future work.

5.2 Bluetooth support for factory automation

Bluetooth [3],[4],[5], IEEE 802.11 [6], IEEE 802.15.4 [7], [8] and the recent WirelessHART standard [9] are currently the main wireless standard protocols for industrial communication. They differ for the PHY and MAC layers, providing different transmission speeds and medium access control policies.

In the IEEE 802.11 family, nodes compete for the medium access according to the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. However, contention-based approaches are not able to guarantee an upper bound on the medium access delay, so they are not adequate for time-constrained traffic. For this reason, other approaches able to provide contention-free access have been developed.

IEEE 802.15.4 provides time slotting and two different operating modes, i.e., the beacon-enabled and the non-beacon enabled one. The beacon-enabled mode supports both a contention-free and a contention-based phase.

WirelessHART adopts the IEEE 802.15.4-2006 at the Physical layer and, on top of that, defines its own MAC layer. Time Division Multiple Access (TDMA) and channel hopping are used to control the medium access. This technique provides collision-free, deterministic communication between two devices [9].

The Bluetooth (BT) technology uses a Master/Slave protocol with a maximum of 7 active slaves for each wireless cell, called a piconet, and adopts a combination of frequency hopping and time division multiplexing (FH-TDM). BT provides several features which make it very suitable for several automation applications. The medium access is co-ordinated by a master, similarly to what happens in many wired fieldbus networks. Thanks to time slotting and to the use of fixed length slots (625 μs), the BT medium access is not only highly deterministic, but also very efficient, as it requires only 1.25 ms for data exchanging (for instance, between a PLC and an actuator). The small size of time slots (as compared to WirelessHART, for instance) is very beneficial to industrial applications, as it allows to support very short cycle times while allowing a high time accuracy, that is quite appropriate for periodic real-time applications. Moreover, frequency hopping, time division multiplexing, Cyclic Redundancy Check (CRC), Header-Error-Check (HEC) and Forward Error Correction (FEC) realize a reliable and robust channel which is suitable for time-critical data transfer [40].

As it is shown in [41], to guarantee the timely delivery of real-time packets and thus to meet their deadlines, deadline-aware scheduling, like the one proposed in [42], has to be introduced, as the BT standard features a master/slave polling mechanism based on round robin which cannot provide any guarantee to real-time communications. Related works [41] and [42] showed that this enhancement is feasible.

BT power consumption is not negligible. However, energy consumption is not a big concern in these environments, as automation applications usually require high duty cycles that prevent the adoption of power saving policies, so, automation devices are typically powered by the electric power line.

The coverage provided by BT (up to 100 meters nominal in version 2.0) is adequate, being comparable to the coverage provided by other wireless standards. As far as the BT bit rate is concerned, 2 Mbps represent a very reasonable value (the IEEE 802.15.4/ZigBee [43] and WirelessHART bit rate is much lower, 250 Kbps) that, combined with the small slot size, allows to efficiently exploit the available bandwidth.

Moreover, in a piconet, the master/slave approach avoids collisions, thus allowing for bandwidth saving,_whereas in IEEE 802.11.b cells (the most common wireless solution currently found in industrial environments), the number of collisions significantly increases with increasing workloads, thus causing bandwidth waste and abrupt throughput degradation.

The long handoff time of the BT protocol [44] limits the support provided for mobility but, with the exception of a few specific applications (for instance, automated guided vehicles), most of typical manufacturing applications do not require mobility support. Even industrial robots typically operate in a limited area within the same wireless cell.

Finally, as far as the number of nodes in a piconet is concerned, actually seven slaves are adequate to the needs of many field-level applications, where each BT node may collect the data originating from multiple devices, thus increasing the quantity of information exchanged. Moreover, several piconets may co-exist and operate in parallel, thanks to the combination of the high number of available channels and frequency hopping, which allows the simultaneous presence of multiple transmissions on different channels.

However, in applications involving a high number of devices and a significant amount of data exchanges, multiple overlapping piconets are needed. In such scenarios, the interference among overlapping piconets has a significant impact on the system performance. For this reason, it is imperative to find a suitable mechanism for managing frequency hopping in such a way that interference is avoided.

5.4 Co-channel interference in Bluetooth

In industrial environments several BT piconets may be located within a limited area. Thanks to the frequency hopping mechanism, Bluetooth could in principle allow the parallel functioning of many (up to 79) piconets, with eight active nodes each (one master and seven slaves) without mutual interference. In practice, however, the statistic probability that two BT piconets will be using the same channel at the same time increases with the density of adjacent piconets.

As co-channel interference depends on the distance between the transmitter and the receiver, if the piconets can be located distant enough from each other, their interference can be reduced or eliminated. However, in large deployments, multiple piconets could be placed in close proximity, thus raising co-channel interference issues.

Some works in literature ([45-47]) studied the interference problem for co-located piconets, focusing on the physical layer and not on the Bluetooth MAC layer.

The paper [48] analyzed the co-channel interference between individual Bluetooth piconets and developed a throughput model, assuming worst-case co-channel interference, based on a Markov chain model. The work showed that throughput deteriorates when the number of piconets increases.

In [49] the authors demonstrated, through a theoretical analysis and numerical simulations, that their approach, called a Dual Channel Transmission (DCT), reduces the Packet Error Rate (PER) due to inter-piconet interference when multiple Bluetooth piconets coexist. The mechanism consists in transmitting a packet over two distinct frequency-hopped channels simultaneously, with a transmission power on each channel being half of the one that would be used in a standard single-channel transmission. The Authors in [49] demonstrated that, when the number of co-located piconets is small, the PER obtained using DCT is significantly lower than the one obtained using the standard approach. However the DCT approach requires modifications to the standard protocol, which make it hard to use.

In the following sub-section the thesis proposes a solution to cope with interference, which exploits the BT protocol peculiarities and does not require changes to the standard protocol. The approach, called a Piconet Management Approach, is described in the next section.

5.3.1.1 The Piconet Management Approach (PMA)

Co-channel interference between pairs (or groups) of BT nodes, operating in piconets close to each other, depends on how the standard frequency-hopping algorithm (SFH) dynamically assigns the transmission frequency to the various nodes. Each time a BT node has to transmit a packet, it runs, at the baseband level, the frequency-hopping algorithm. This algorithm, on the basis of the master MAC address and its clock, calculates an index ranging from 0 to 79 which selects the corresponding frequency. This way the transmission frequencies are assigned in a pseudo-random way.

Let us examine a typical scenario for industrial environments, such as the one represented in Fig. 5.1, it simplifies the network architecture shown in chapter 2.

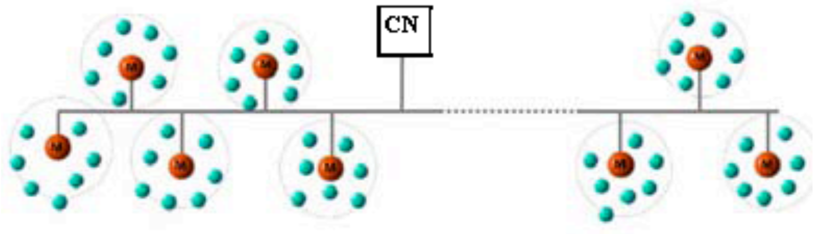


Figure 5.1: Network scenario

In this scenario a controller node (CN) coordinates several independent automation cells (ACs), made up of several BT piconets interconnected through a real-time wired backbone. Each piconet represents a manufacturing cell or part of an automation system.

According to the approach here proposed, the Piconet Management Approach (PMA), the CN coordinates the piconets with the purpose of minimizing the interference. The PMA allows the CN to synchronize the clocks of the piconets and manage the frequencies in order to limit interference between adjacent cells.

This result is accomplished introducing a variant in the standard frequency-hopping algorithm (SFH), which can be implemented without requiring significant hardware modifications. Fig. 5.2 shows the block diagram of the hop selection module (the selection box), according to SFH.

The selection box maps the inputs to a particular hop frequency. Basically the inputs are the master clock and part of the MAC address. The MAC address is fixed (once a master has been chosen), whereas the clock varies continuously (one tick every 312.5 ms).

This way, the combinatorial logic network inside the selection box provides, every 312.5 ms, a new value that selects in a pseudo-random fashion a new frequency value.

The master clock is encoded using 28 bits, but in connection state only the 27 most significant bits are used (this makes a clock tick 625 ms long). All the 28 bits are used, instead, in the page and inquiry states. Each BT unit has a 48-bit address (BD_ADDR, Bluetooth Device Address) according to the addressing formats of IEEE 802.15.1 standards and divided into 3 parts: the LAP (lower address part, 24 bits), the UAP (upper address part, 8 bits), the NAP (non-significant address part, 16 bits).

The input address for the selection box is made up of 28 bits, the entire LAP plus the 4 least significant bits of the UAP.

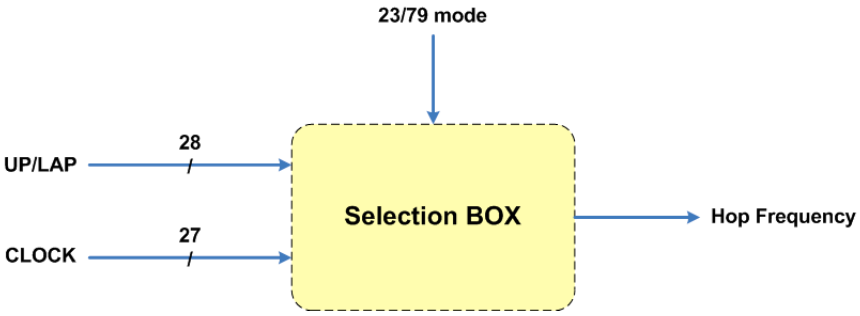


Figure 5.2 SFH – block diagram of hop selection

We assessed the SFH behaviour by executing a long sequence of SFH runs. To this aim we implemented the logic network inside the selection box, providing the UAP/LAP MAC address and the clock values. Then, for each frequency (from channel 1 to channel 79) we measured the number of hops after which the same frequency is selected again.

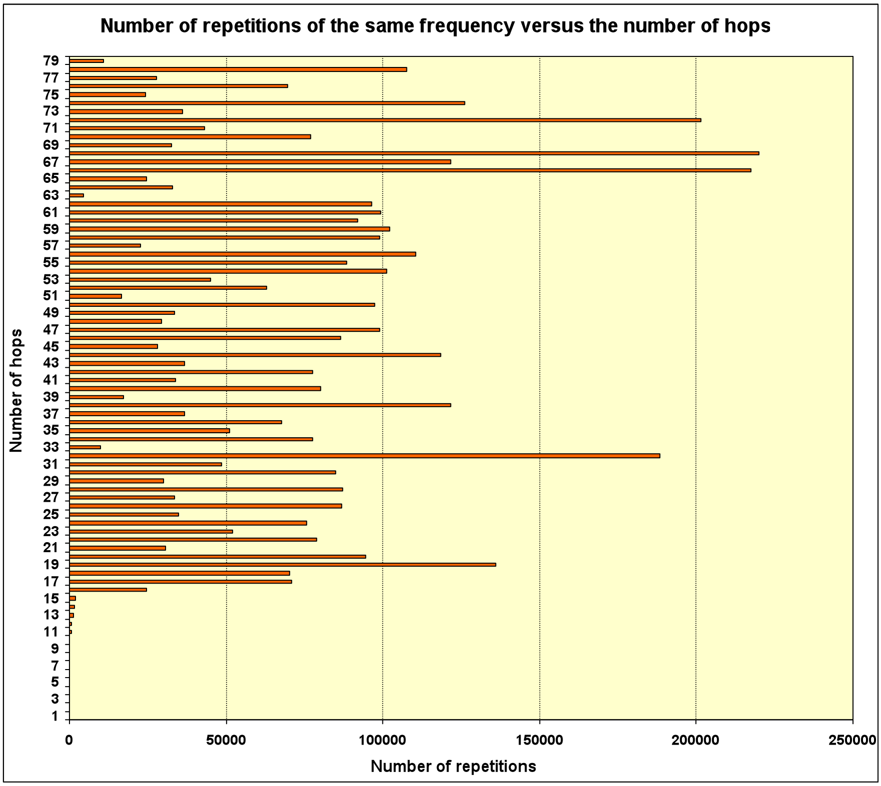


Figure 5.3 Number of repetitions of the same frequency versus the number of hops

The graph in Fig. 5.3 shows on the X axis the number of recurrences of a given frequency versus the number of hops required before the same channel is selected again (Y axis). The graph refers to a master generating for 24 hours a sequence of transmission frequencies by using the SFH algorithm. The 24-hour interval is long enough to explore the entire sequence of frequencies generated for a given MAC address and a given starting frequency. The SFH runs have been repeated for many different values of MAC addresses and starting frequencies, always obtaining results quite similar to those shown in Fig. 5.3. From the results found we concluded that, for every frequency in the range from 1 to 79, any frequency shows up again after at least 10 hops and recurs with a very low probability after 11-15 hops.

From the results obtained, we inferred that the behaviour of the SFH algorithm can be used, with minor modifications, in order to improve the BT performance and eliminate the co-channel interference.

Let us consider again the network shown in Fig. 5.1. There are several piconets, but no scatternets (as scatternets proved to be difficult to implement and inefficient, so they are not used in real applications). Here we assume that all the masters of the piconets share the same clock and MAC address, in order to generate the same hopping sequence. In these conditions, the maximum inter-cell interference would be experienced and the system would be unable to correctly operate. However, as said before, the investigation of the SFH behaviour revealed that each frequency does not recur before a certain number of hops, independently of the MAC address of the master considered. In particular, all the SFH runs have shown that no frequency recurs before 10 hops, and any frequency recurs with a very low probability after 11-15 hops (Fig. 5.3). Here we exploit this feature in order to reduce the co-channel interference.

Two conditions have to be satisfied in order to achieve this result. First, all the masters have to be synchronized with the CN. This is an external synchronization and the reference clock must be provided by the CN. Although this approach is not foreseen in the BT protocol, it does not contrast with the operational modes provided in the standard. The synchronization of all the master clocks with the controller clock can be performed with high precision through the backbone, using one of the clock synchronization algorithms available in the literature, such as [50]. Several switches have been developed which provide synchronization functionalities based on the IEEE 1588 Precision Time Protocol [51].

The second condition to be fulfilled is that all the masters, while generating the hopping sequence, must refer to the same MAC address provided by the CN. This will allow all the masters to generate the same frequency hopping sequence.

The PMA approach allows the piconets to correctly operate, sharing the same hopping sequence, provided that they are shifted, i.e., that each piconet follows the hopping sequence with a given offset set by the CN, as it is shown in Fig. 5.4. It is the CN responsibility to assign each master a suitable shift in order to allow all the piconets to generate non-overlapping channel sequences. Each master, once it is synchronized with the CN and has received the common MAC address, has to store its offset value into a suitable register. Every time a master runs the FH algorithm, it adds the shift value to the clock, thus shifting the channel sequence.

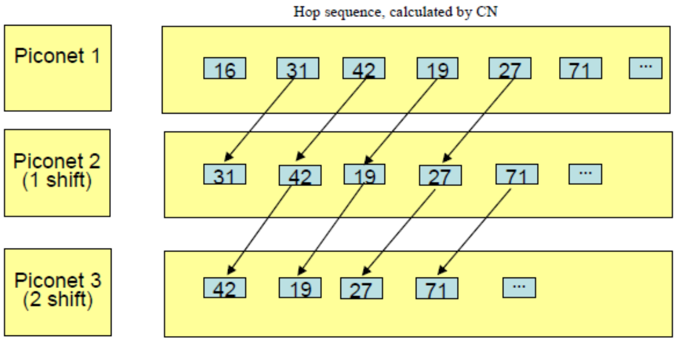
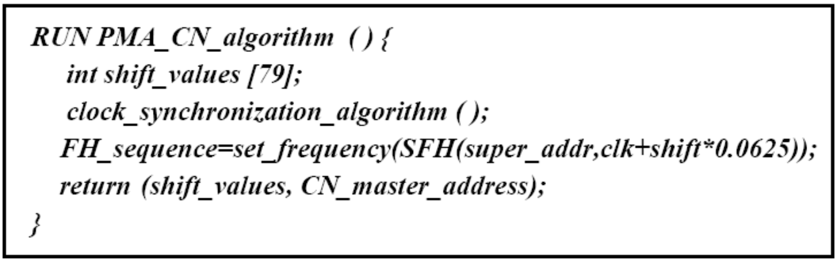


Figure 5.4: Hop sequence shift

The same approach has to be followed by all the slaves belonging to the same piconet.

The network correct operation requires that all masters are synchronized with the CN clock. However, any inaccuracy of the clock synchronization cannot lead to the overlap of two adjacent slots in close piconets, because each slave interrupts its transmission after about 2/3 of a slot, as required by frequency hopping. Therefore, even if the next slot would start some microseconds in advance, this will not cause collisions between adjacent slots.

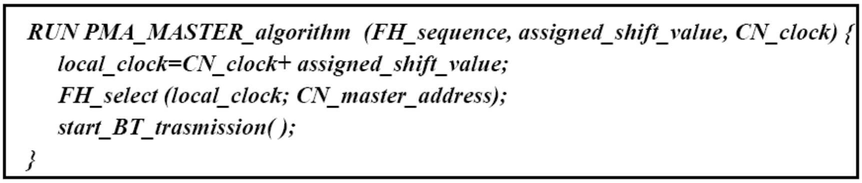
The CN invokes the *PMA_CN_algorithm* (Fig. 5.5) in order to synchronizate the masters and select the suitable shift value for each master.



```
RUN PMA_CN_algorithm  ( ) {
    int shift_values [79];
    clock_synchronization_algorithm ( );
   FH_sequence=set_frequency(SFH(super_addr,clk+shift*0.0625));
   return  (shift_values, CN_master_address);
}
```

Figure 5.5. The PMA algorithm run in the CN

Each master, before passing the packet to the physical level, invokes the *PMA_Master_algorithm* (Fig. 5.6) to generate the shifted frequency sequence.



```
RUN PMA_MASTER_algorithm  (FH_sequence, assigned_shift_value, CN_clock) {
    local_clock=CN_clock+ assigned_shift_value;
    FH_select (local_clock; CN_master_address);
    start_BT_trasmission( );
}
```

Figure 5.6: The PMA algorithm run in the master node

The sequence diagram in Fig. 5.7 shows how the network nodes of Fig.1 cooperate. The CN, via the wired backbone, synchronizes the clock of the relevant masters and sends them its own MAC address (super_address) and the shift value corresponding to each master. The masters store such values into local variables calling the *set_super_addr(super_address, shift_value)* function. Then, according to the standard BT protocol, the master starts transmitting, sending the hopping sequence to its slaves.

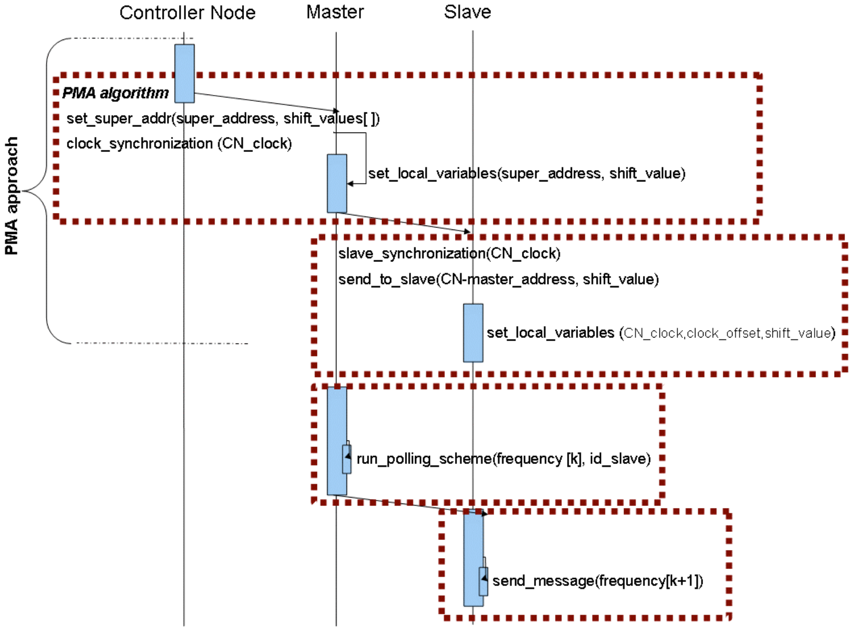


Figure 5.7: PMA approach sequence diagram

The synchronized masters maintain the values received from the CN into local variables so that, when they will calculate their hopping sequence, they will obtain the same values foreseen by the CN.

The PMA can obtain null co-channel interference by means of a proper shifting of the generation sequence of the hopping frequency of each piconet (see Fig. 5.4). However, this holds only when the number of close piconets does not exceed 10 since, as shown in Fig.3, we cannot guarantee that the same frequency will not be generated again after more than 10 hops.

In the case of many overlapping piconets, the PMA is able to reduce the interference, but not to completely avoid it.

However, it has to be underlined that, in typical industrial scenarios, 10 overlapping piconets (i.e., cells less than 10 meters apart from each other) in a limited area is already a significant number. At design time, therefore, it is possible to avoid co-channel interference, by a careful planning of the network deployment able to limit to ten the maximum number of overlapping cells handled by the PMA. If several clusters, made up of up to ten overlapping piconets, are conveniently placed in a large system, a high degree of parallelism can be achieved with a null co-channel interference.

Moreover, it is possible to make each BT node gather data from multiple devices (sensors, etc.), so as to increase the amount of transmitted data.

A reduction of co-channel interference entails smaller delays, as packet re-transmissions are avoided, thus we expect that the PMA will provide reduced delays and increased throughput. We investigated the performance of our mechanism by simulation.

5.3.2 Performance Evaluation

To assess the performance of the PMA mechanism, we run ns-2 simulations, using the ucbt-0.9.9.2 module [52] that implements the BT protocol stack. In our evaluation, only mono-slot transmissions are considered, as they better fit the timeliness requirements of the envisaged industrial application. The scenario shown in Fig 5.3 relates to a wired backbone, connected to a maximum of 25 master nodes coordinated by a controller node. Each master can be connected up to a maximum of 7 slaves, thus creating a piconets.

As the backbone does not influence the co-channel interference assessments, it has been implemented by means of cascaded Ethernet switches. This way, each pair of nodes is connected, while keeping the collision domains separate.

In the considered scenario, each piconets features 7 active slaves and a generation period for periodic packets equal to 10 ms. The total periodic traffic generated by each slave in a piconets is 0.12 Mbps.

The following graphs compare the performance of the standard SFH with the one of the PMA approach with a varying number of piconets connected to the backbone.

Fig. 5.8 shows that the PMA obtains a higher throughput than the standard SFH. This is due to the co-channel interference reduction. As there are no packets damaged because of co-channel interference (or, in the case of more than 10 overlapping piconets, the number of such packets is small), the piconets masters do not have to perform re-transmissions, thus saving bandwidth for data transmissions.

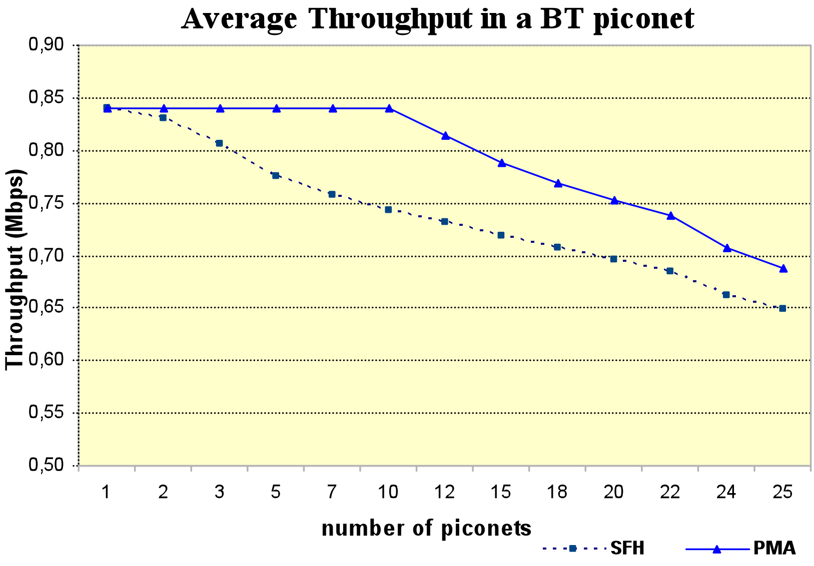


Figure 5.8: Piconet average throughput vs. the number of piconets

Fig. 5.9 shows the packet loss percentage, due to co-channel interference, versus the number of piconets. The graph shows that the number of packets collisions due to co-channel interference is equal to zero if a few piconets are activated (up to the maximum number found by adopting the PMA approach). Such a value grows with the number of piconets, as the probability that multiple piconets will be transmitting at the same frequency increases too.

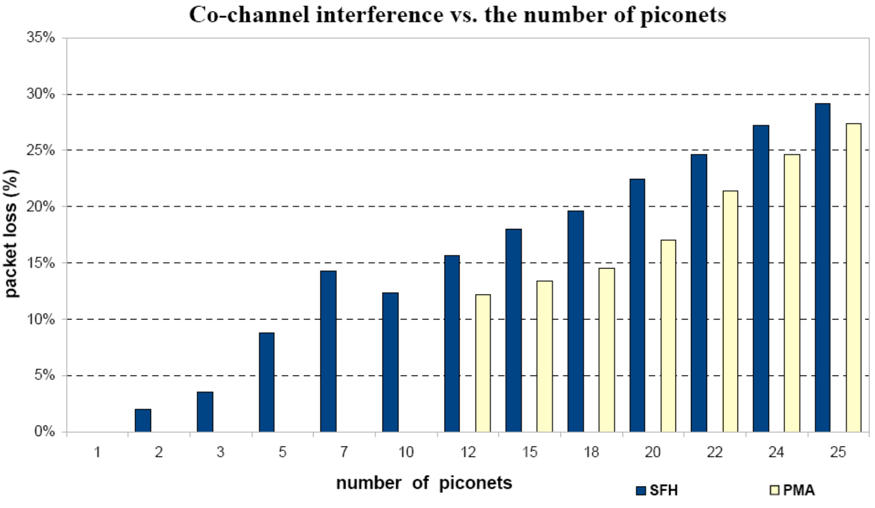


Figure 5.9: Co-channel interference vs. the number of piconets

Another benefit of the PMA is the packet delay reduction, as shown in the graphs of Fig. 5.10 and 5.11, which compare the minimum and maximum delay obtained by PMA and the ones obtained by the BT SFH approach, respectively.

The delay reduction is obtained thanks to the piconet synchronization combined with frequency management, that together reduce the co-channel interference and the number of collisions. With reference to Fig. 5.10 we can observe that, with PMA, the minimum delay grows abruptly when the number of piconets exceeds 10, reaching values close to the SFH ones.

In general, the delay reduction becomes less significant when the number of overlapping piconets exceeds the limit computed by the PMA, as the interference probability increases.

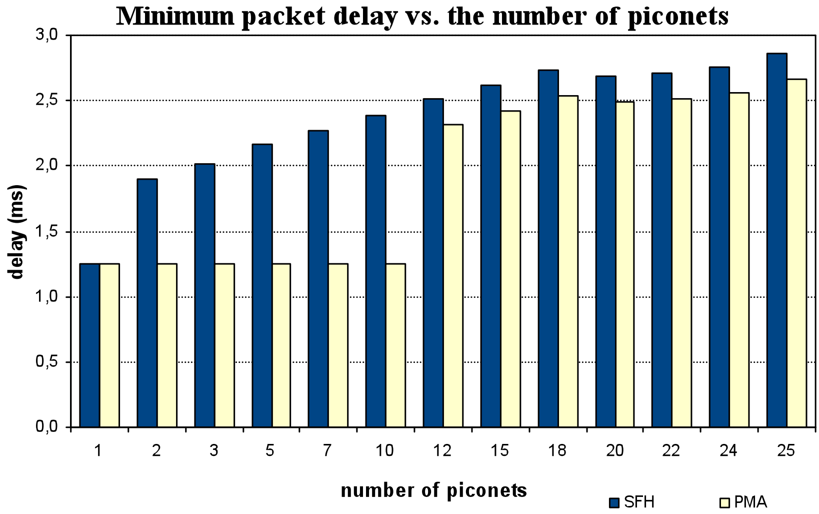


Figure 5.10: Minimum packet delay vs. the number of piconets

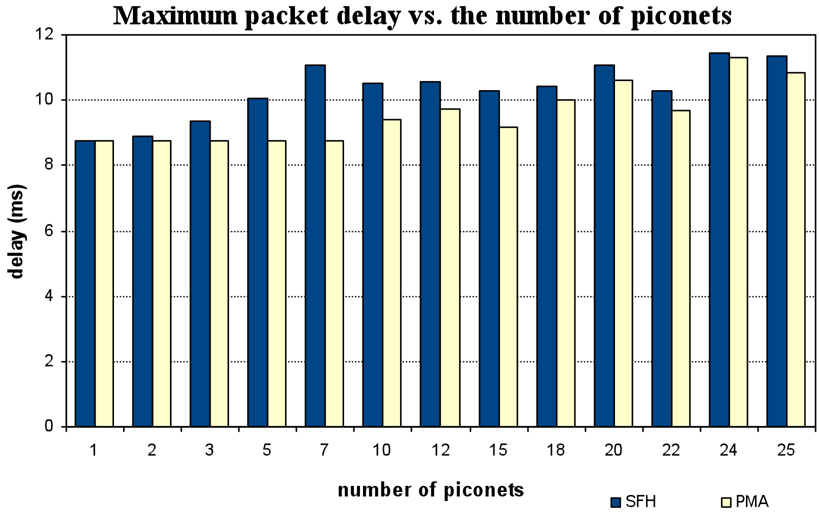


Figure 5.11: Maximum packet delay vs. the number of piconets

5.3.2 A deadline aware intra wireless cell scheduling

To satisfy some the industrial system requirements, two scheduling levels are implemented. The first level is Local Scheduling (LS), performed inside the local queues of each BT device. We assume that, to support real-time traffic, LS is handled in each device in an EDF fashion. The second level, called Intra-Piconet Scheduling (IPS), refers to the scheduling policy used within the piconet. In order to support real-time communication, deadline-aware policies should also be implemented at the IPS level.

As in [54], we assume that traffic exchanges are known a priori, at least for periodic variables. This is typical of an industrial communication scenario, where the Master could be configured by an operator or acquire a configuration file from a database. As far as aperiodic traffic is concerned, we assume a *signaling scheme*, where Slaves communicate their queue status while transmitting packets to the piconet Master. This information is entered into a specific packet field of the slot sent to the Master, e.g., the flow bit in the header, as in [55].

For the sake of simplicity, we assume that each Slave produces one periodic variable (with a fixed period and deadline equal to the period) and one aperiodic variable, both of known size. Each Slave therefore manages two distinct queues (buffers) for periodic and aperiodic variables. However, this simplifying assumption is not mandatory: if several different periodic and aperiodic variables are produced by each Slave, several distinct traffic classes, together with the relevant message queues, will be implemented. In this case, to provide QoS support (i.e., differentiated services for different traffic classes) a priority-based mechanism can be used to poll the different queues.

The S/S communication mode described can be integrated with the functions already present in the BT standard. The implementation of new functions does not require any HW modification to the BT Baseband chip. Only modifications in the firmware are needed to implement the functions needed for S/S communication. These modifications could be steadily implemented in the BT chip and then used by applications which can take advantage of them [54].

5.3.2.1 The proposed approach

The approach proposed here, called M/S(EDF/CBS)+ S/S(EDF), exploits parallel M/S and S/S communications to provide integrated support for deadline-aware scheduling of all traffic, both periodic and aperiodic. More specifically, S/S communications support transmissions relating exclusively to periodic traffic, while M/S transmissions serve stations generating hybrid traffic, i.e., both periodic and aperiodic traffic. In addition, to make scheduling deadline-aware, periodic traffic is scheduled using the Earliest Deadline First (EDF) algorithm [35], while aperiodic transmissions are handled by a dynamic-priority server, i.e., the Constant Bandwidth Server (CBS) [56].

Periodic traffic scheduling

EDF is a dynamic-priority real-time scheduling algorithm that assigns scheduling requests (in this case, requests for transmission of the periodic variables relating to the process being controlled) a priority that is inversely proportional to their respective absolute deadlines. Given a request for a periodic transmission arriving at time r_i, with a relative deadline D_i (which represents the time interval, measured from the arrival of the request, within which the variable has to be transmitted) equal to the period T_i, the absolute deadline d_i will be :

$$d_i = r_i + D_i$$

Periodic requests are served according to EDF. Based on the knowledge of the dynamics of the periodic variables produced by the various Slaves, the Master performs EDF polling in the M/S mode in the sub-piconet, and configures S/S transmission scheduling according to EDF in the ring.

Aperiodic traffic scheduling

Slaves which have also aperiodic traffic to transmit signal their request for an aperiodic transmission while transmitting periodic packets, setting the flow bit in the header of the slot sent to the Master. The Master, upon receiving such a request, handles it according to the CBS rule.

Two parameters are used in the CBS: the period Ts and the capacity Qs, which represents the maximum budget a request can consume in each period. The Qs/Ts ratio represents the bandwidth of the server, U_s. The server also manages two internal variables: the current budget at time t, cs, and the current deadline assigned to a request, ds. Both are by definition initialized to zero.

In our approach, the CBS parameters are handled by the Master. Each aperiodic request is assigned a budget, equal to the capacity of the server, Qs, and a initial relative deadline equal to the period of the server, Ts. If the budget is sufficient, the request will terminate within the assigned budget. If the Master receives a request for aperiodic transmission while another request is still active, the new arrival is placed in a server queue. When the active request is completed, the Master checks whether the server's residual budget is sufficient (we recall that transmission scheduling is not preemptive). If it is, it extracts the first element in the queue and schedules it with the current deadline and capacity.

When the budget runs out ($cs = 0$), it is replenished to the max value Qs by setting $cs=Qs$, and the current deadline is postponed by a period, setting $ds = ds+Ts$.

If the server is idle when a request arrives at time t the Master checks whether it is possible to “recycle” the server’s budget and current deadline. It checks whether the inequality $cs < (t-ds)(Qs/Ts)$ is verified. If it is, the request can be scheduled with the current values for the server; otherwise cs has to be reset to the max value Qs and the deadline is recalculated setting $ds = t+Ts$.

Further details of CBS can be found in [56].

5.3.2.2 Comparison with previous work

There are two main differences between the approach in [54] and the one proposed here:

- the use of M/S communication in [54] and parallel M/S and S/S communication here;
- the use of a different type of dynamic-priority server for aperiodic traffic scheduling: TBS in [54] and CBS here.

As regards the use of parallel M/S and S/S operating modes, it should be observed that by combining the two the network is able to support a higher workload.

The parallelism between the M/S and S/S modes and the relatively long duration of the logical ring mean that there is more available bandwidth than there would be if all nodes operated in the M/S mode.

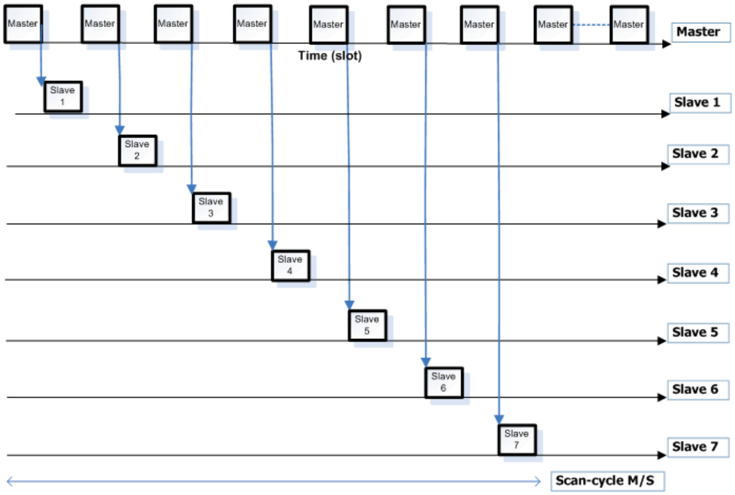


Figure 5.12: M/S Communication

In addition, thanks to the fact that the S/S mode makes it possible to eliminate the Master polling slot, the scan cycle for a control loop can be significantly shortened, as can be seen by comparing Fig. 5.12 (which refers to the standard BT M/S mode) and Fig. 5.13 (which illustrates the shortened scan cycle realized by the proposed parallelism between M/S and S/S). A shorter scan cycle makes it possible to support control loops with a faster dynamics. In addition, as shown in [82], it enhances the schedulability of real-time traffic.

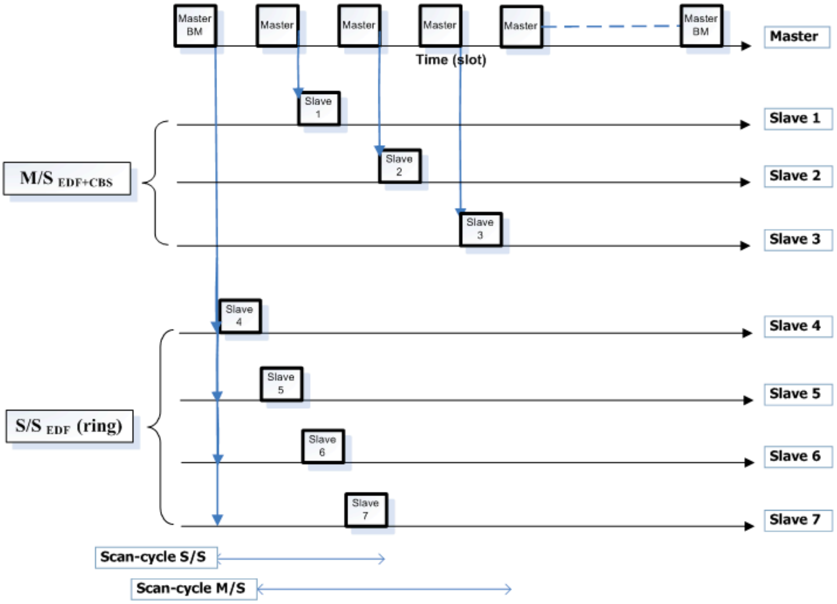


Figure 5.13: Parallel Master/Slave and Slave/Slave communication

A further advantage of operating in the S/S mode is that it reduces the reception/transmission overhead introduced by passing through the protocol stack of the nodes involved in communication (this overhead includes control of correctness, buffering time, packet assembly, etc.). In the M/S mode, the overhead on the communications between two Slaves comprises the contributions of the two Slaves and that of the Master. As S/S communication is direct, there is no Master overhead.

The choice of CBS instead of TBS [57], [58] was made on the basis of comparative assessments on the two mechanisms in the specific context dealt with here. As each transmission in the M/S mode entails a polling slot sent by the

Master, the duration of an aperiodic transaction is C_i+C_m (where C_i is the duration in slots of the aperiodic transmission and C_m is equal to one slot, the polling slot used by the Master to address the Slaves). CBS assigns aperiodic requests a number of slots equal to Qs for each server period Ts.

Considering that:

a. transmission scheduling is not preemptive,
b. Bluetooth has a slotted canne,
c. a transmission can only take up 1, 3 or 5 slots, by sizing Qs as equal to the maximum possible duration of an aperiodic transaction, i.e. Qs=1+5=6 slots, using CBS it is possible to transmit a number of aperiodic variables ranging from 1 (if C_i=5 slots) to 3 (if the 3 requests C_i are all of 1 slot) with the same server deadline. TBS, on the other hand, assigns each aperiodic request R_i increasingly higher deadline values on the basis of the following formula:

$$\mathrm{d}_\mathrm{i} = \max\left(t_i, \mathrm{d}_{\mathrm{i-1}}\right) + \frac{C_i + C_m}{U_s}$$

It is known in the literature that TBS is not robust to execution overruns, if no exact knowledge on the maximum service time of the processed requests is available. However, in Bluetooth networks used in industrial communications, the Master device knows the maximum size of an aperiodic traffic request (5 slots). So, in case of multislot transmissions, to be on the safe side, the deadline for each aperiodic request R_i can be postponed, on the basis of the previous formula, on account of the maximum possible duration of an aperiodic transmission and not on its actual duration C_i. As a result, when aperiodic traffic is heavy, with short interarrival times between consecutive requests, TBS increases the average response time of aperiodic requests, which is shorter if scheduling is based on the CBS mechanism.

5.2.3.3 Performance Evaluation

In this section we will evaluate the validity of the proposed $M/S_{(EDF+CBS)}+S/S_{(EDF)}$ approach and compare it with the standard BT. The evaluation was performed in various scenarios, considering both simple piconets in which real-time traffic is produced by a few slaves (e.g. simple configurations with only a few sensors and one actuator) and more complex piconets with seven Slaves (the maximum allowed by the BT protocol). The evaluation was carried out by means of an ad hoc simulator that implements the communication and scheduling models presented here.

The scenarios differ in their time constraints, the periodic and aperiodic workload and the number of Slaves, so as to represent situations with varying degrees of complexity. Various configurations were investigated for each scenario, featuring the same amount of periodic traffic and different amounts of aperiodic traffic. In all the tests described below, the aperiodic traffic was generated assuming the existence of a minimum interarrival time between two consecutive aperiodic requests. This is equivalent to considering aperiodic traffic as sporadic, so we will henceforward refer to sporadic traffic. In the various configurations the minimum interarrival time for sporadic requests was made to vary between a minimum value of 3125 µs (corresponding to 5 slots) and a maximum of 62500 µs (corresponding to 100 slots).

Scenario 1

Let us consider a simple configuration with four Slaves and one Master and real-time transmission of periodic and sporadic traffic, as in Fig. 5.14.

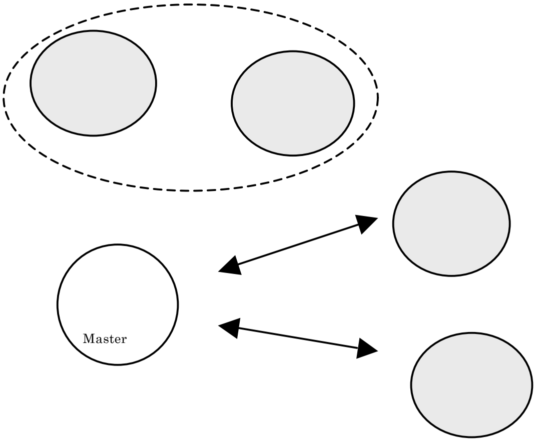


Figure 5.14: Piconet in Scenario 1

Slaves A and B only exchange periodic traffic, while Slaves C and D transmit both periodic and sporadic traffic. Table I summarizes the requirements of the variables transmitted.

TABLE I. SCENARIO 1

	Periodic Traffic		***Sporadic Traffic***
	T_i (μs)= D_i (μs)	***C_i (μs)***	***Minimum interarrival time (μs) → Min-Max, number of slots***
Slave A	3750	625	None
Slave B	5625	625	None
Slave C	7500	625	3125 to 62500, 1 slot
Slave D	8125	625	3125 to 62500, 1 slot

Fig. 5.15 shows the periodic and sporadic workload generated, the throughput obtained with standard BT and that obtained using our approach. The periodic workload is as indicated in Table I, the sporadic workload refers to an average interarrival time of 15625 μs, which loads the network heavily, but does not saturate it.

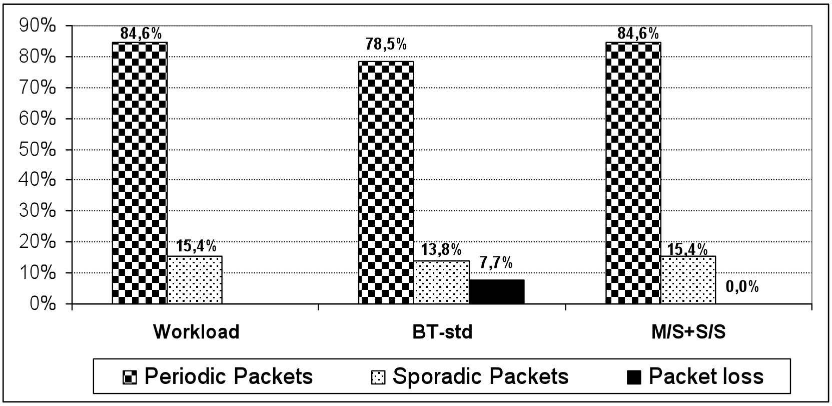


Figure 5.15: Throughput vs. workload in the two approaches in Scenario 1

As Fig. 5.15 shows, the standard BT exhibits a loss of periodic and sporadic traffic, represented by the variables not transmitted, as they either remain in the queue when the simulation terminates (i.e., after 30 s) or are overwritten by the new value. The packet loss represents the difference between the number of variables generated for transmission and those that actually reach their destination. The periodic packet loss depends on the fact that the scheduling algorithm used by the standard BT, a Round-Robin, does not assign priorities or take deadlines into account, and places all the Slaves on the same level. Periodic and sporadic traffic thus receive the same treatment.

Besides the packet loss shown in Fig. 5.15, it is also necessary to consider the presence of 8,61% deadline misses by the periodic traffic transmitted (Fig. 5.16, fouth column). This means that 8,61% of the periodic throughput in Fig. 5.15 represents packets that had already expired on reaching their destination.

Fig. 5.16 shows the periodic packet deadline miss values obtained by the standard BT in the scenario considered, with varying amounts of sporadic traffic. The increasing sporadic traffic values on the x-axis are represented in terms of “Periodic packets sent”, he value of which decreases as the amount of sporadic traffic increases. Fig. 5.16 shows that the percentage of missed deadline remains more or less constant. The deadline miss percentages observed are significant.

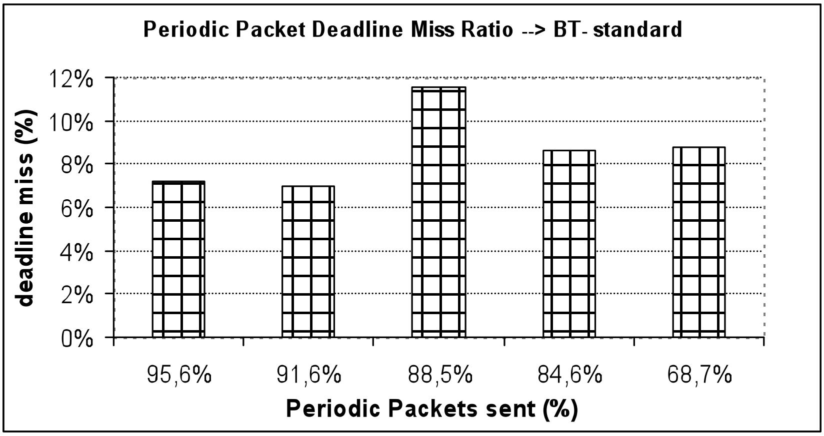


Figure 5.16: Periodic Packet DM Ratio

The M/S(EDF+CBS)+S/S(EDF) approach, on the other hand, allows all the periodic packets transmitted to meet their deadlines. This is possible thanks to the larger amount of bandwidth made available by the parallelism between the logical

S/S ring and the sub-piconet operating in the M/S mode, and the use of CBS. Zero deadline miss values are obtained for periodic traffic even when the percentage of sporadic traffic increases. This demonstrates the validity of the combined approach to real-time scheduling proposed here. The periodic traffic is, in fact, well isolated thanks to the CBS, which does not allow sporadic traffic to go beyond the bandwidth it has been assigned. As the amount of sporadic traffic increases, the standard BT approach, on the other hand, is not only unable to achieve a zero deadline miss (as shown in Fig.5.16) but, and above all, it is unable to send all the periodic packets generated, as shown in Fig. 5.17.

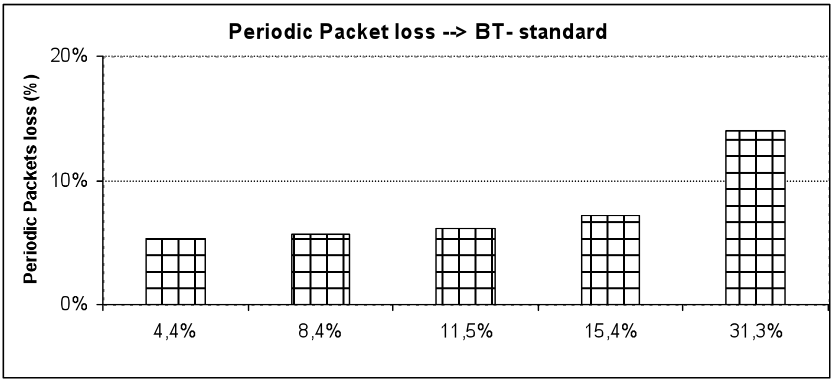


Figure 5.17: Periodic Packet Loss

As regards the average delay for sporadic traffic, the tests carried out (the results of which are given in Fig. 5.18) show that the standard BT experiences a decidedly higher delay than the $M/S_{(EDF+CBS)}+S/S_{(EDF)}$ approach. The latter allows for better exploitation of the available bandwidth, as shown in Fig. 5.18, where saturation occurs with a much higher sporadic workload.

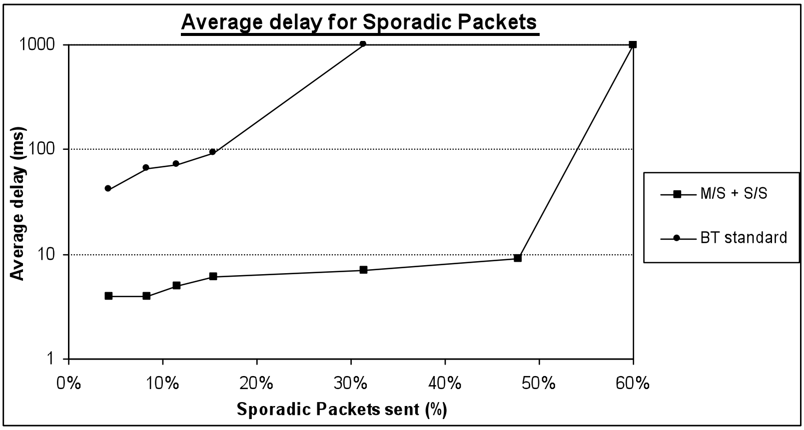


Figure 5.18: Average delay for sporadic packets

Scenario 2

The second scenario features the presence of seven Slave.

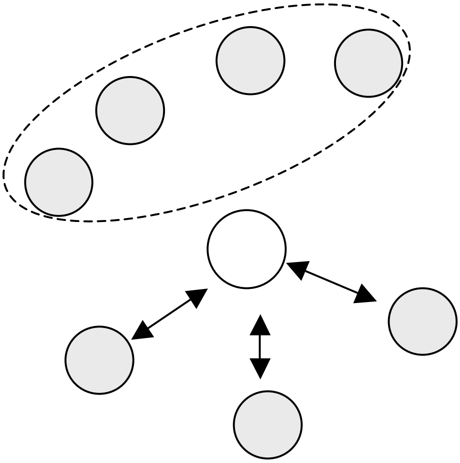


Figure 5.19: Piconet in scenario 2

Slaves A, B, C and D only produce periodic traffic, while Slaves E, F and G transmit both periodic and sporadic traffic, as indicated in Table II.

TABLE II. SCENARIO 2

	Periodic Traffic		***Sporadic Traffic***
	Ti (µs)= Di (µs)	***Ci (µs)***	***Minimum interarrival time (µs) → Min-Max, number of slots***
Slave A	13125	625	None
Slave B	12500	625	None
Slave C	11250	625	None
Slave D	10000	625	None
Slave E	8750	625	3125 to 62500, 1 slot
Slave F	8125	625	3125 to 62500, 1 slot
Slave G	7500	625	3125 to 62500, 1 slot

Fig. 5.20 shows the offered workload and the throughput obtained using the standard BT and our approach in this scenario. The results for the various types of traffic were obtained with a constant periodic workload and an average sporadic traffic interarrival time of 15625 µs (i.e. 25 slots).

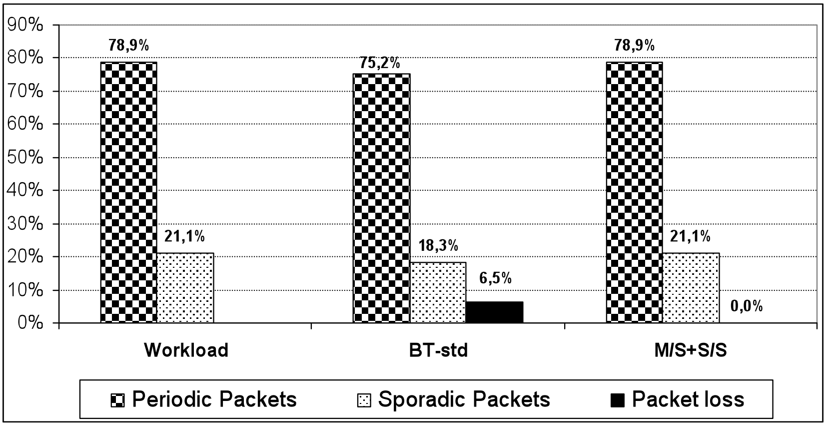


Figure 5.20: Throughput vs. Workload with the two approaches in Scenario 2

Here, as in the previous case, the standard experiences a packet loss of 6,5%. The figure also shows the loss of a fraction of the sporadic packets generated (0.2%).

The $M/S_{(EDF+CBS)}+S/S_{(EDF)}$ approach allows all the periodic packets to be transmitted and they all meet their deadlines. This is also confirmed when the percentage of sporadic traffic varies, leaving the amount of periodic traffic unaltered. The $M/S_{(EDF+CBS)}+S/S_{(EDF)}$ approach also allows all the sporadic traffic to be sent, thanks to the larger amount of bandwidth made available by the M/S+S/S parallelism which, with the same workload, offers a higher throughput.

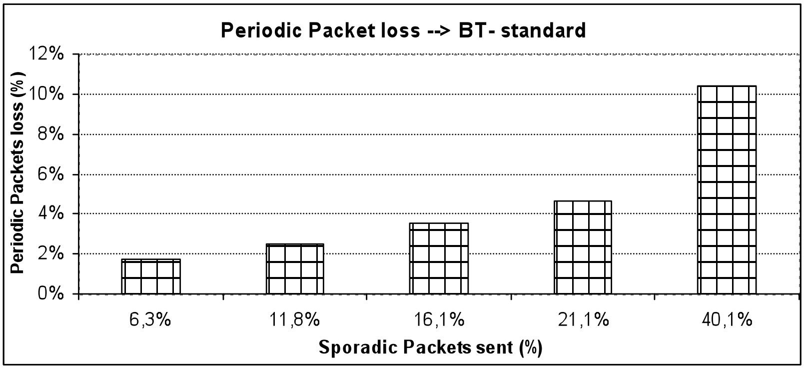


Figure 5.21: Periodic packet loss

Fig. 5.21 gives the periodic traffic packet loss values obtained by the standard BT with varying amounts of sporadic traffic generated in the various configurations considered in this scenario and a constant amount of periodic traffic. Fig. 5.22 shows that the standard BT has non-null periodic packet deadline miss values for all the configurations considered.

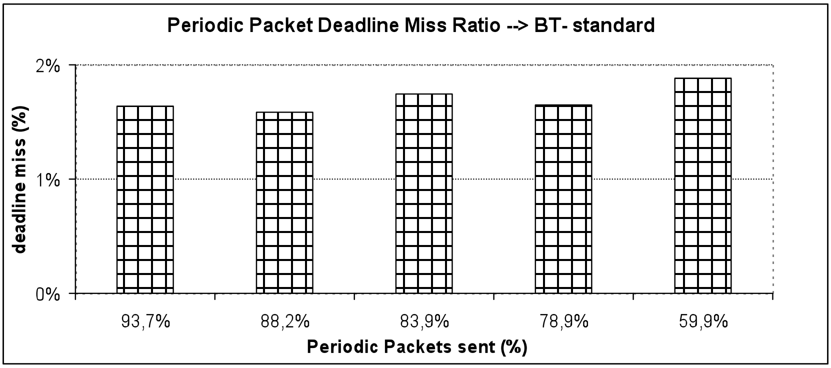


Figure 5.22: Periodic Packet Deadline Miss Ratio

Fig. 5.23 shows the average delay for sporadic traffic as the workload increases. Here, the values expressed by the curve referring to the standard BT approach only have a qualitative value (they show the great difference in delay times as compared with the M/S+S/S approach), as they were obtained (excluding the first value) when the bandwidth was saturated and so in non-stationary conditions. However, it is evident the significant difference between the values obtained by the two approaches.

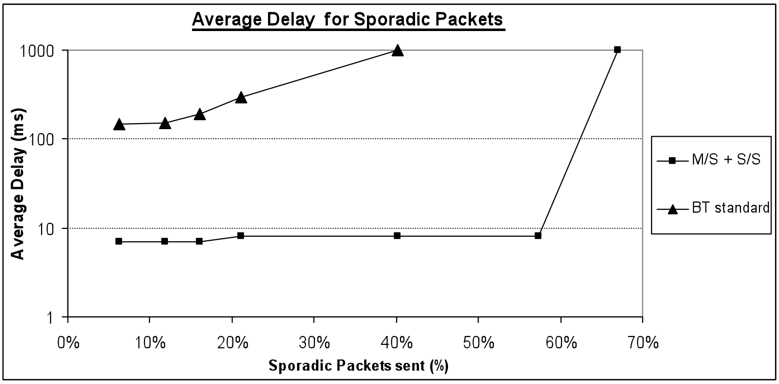


Figure 5.23: Average delay for sporadic packets

Scenario 3

In this scenario the network comprises seven Slaves (as in Fig.5.19), but the traffic patterns are different, as indicated in Table III, and made up of multislot packets.

TABLE III. SCENARIO 3

	Periodic Traffic		***Sporadic Traffic***
	T_i (μs) =D_i (μs)	***C_i (μs)***	***Minimum interarrival time (μs) → Min-Max, number of slots***
Slave A	18750	1875	None
Slave B	17500	1875	None
Slave C	15625	625	None
Slave D	13750	625	None
Slave E	13750	1875	3125 to 62500, 3 slots
Slave F	12500	1875	3125 to 62500, 3 slots
Slave G	11250	625	3125 to 62500, 3 slots

This scenario differs from the previous one because the duration of the transmissions varies from 1 to 3 slots. Here we present the results obtained considering an average interarrival time for sporadic traffic of 15625 μs (25 slots) and some results obtained in this scenario with varying amounts of sporadic traffic.

Fig. 5.24 shows the workload produced and the throughput obtained by the standard BT and our approach, with the periodic workload values shown in Table III and sporadic traffic with an interarrival time of 15625 μs.

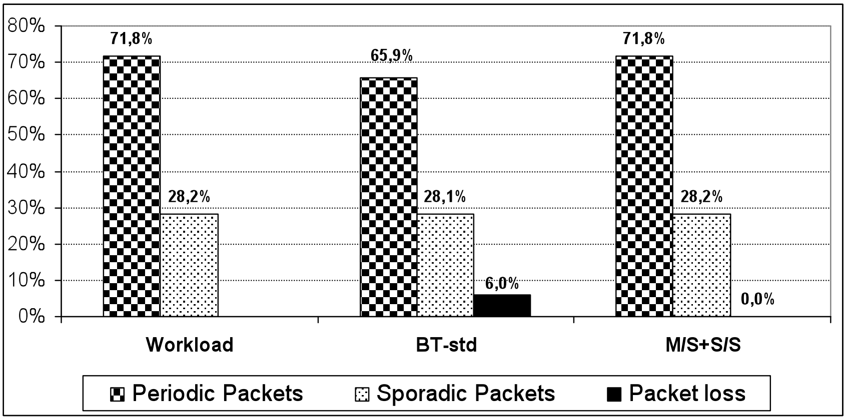


Figure 5.24: Throughput vs. workload for the two approaches in Scenario 3

As can be seen, the standard BT introduces a periodic packet loss of 6%. In addition, 1.39% of the periodic traffic transmitted is affected by deadline misses.

With the M/S(EDF+CBS)+S/S(EDF) approach, on the other hand, there is no packet loss and all the periodic packets meet their deadlines. Similar results are shown by the graphs in Figs. 5.25 and 5.26, which were obtained with standard BT by varying the amount of sporadic traffic. In all cases the standard BT has non-null deadline miss and packet loss values, which grow as the sporadic workload increases.

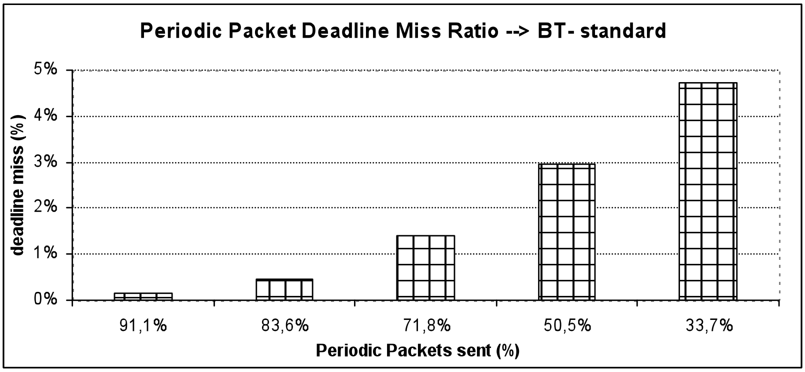


Figure 5.25 Periodic Packet Deadline Miss Ratio

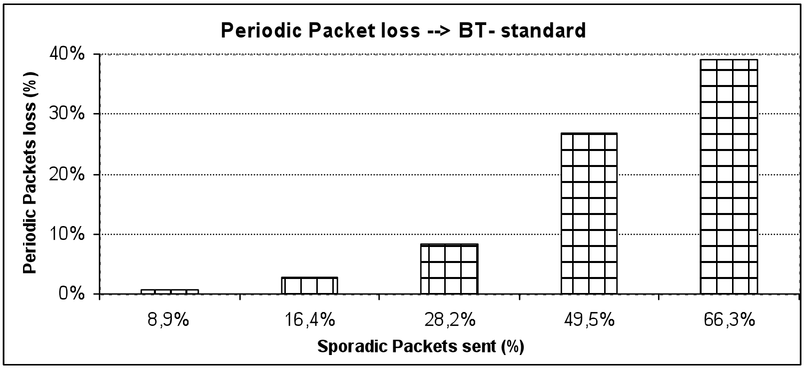


Figure 5.26: Periodic Packet loss

Average delays obtained for sporadic traffic are shown in Fig. 5.27. The standard BT approach has a very high average delay compared with the M/S(EDF+CBS)+S/S(EDF) approach. If we compare these results with those given in Fig. 5.18 for Scenario 1, we notice that the network behaves differently. The standard BT here reaches saturation more slowly, thanks to the use of multislot transmissions which enhances the efficiency of the protocol, but the average delay values are higher, due to the larger number of slots taken up by sporadic traffic.

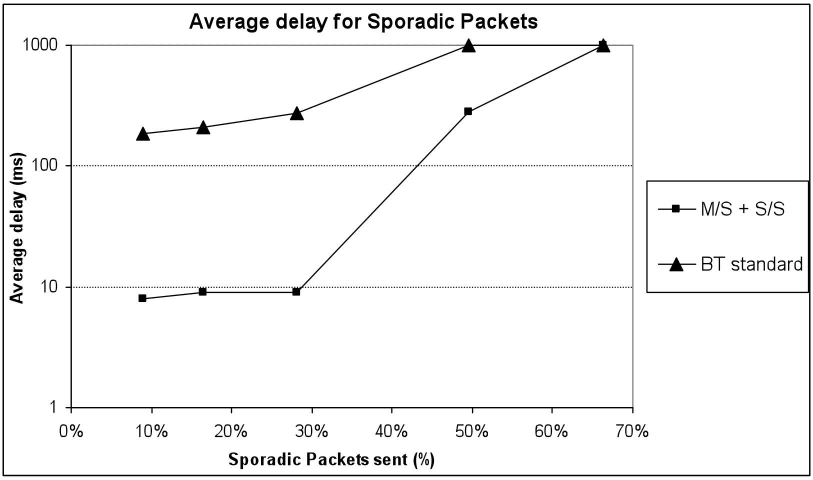


Figure 5.27: Average delay for sporadic packets

5.3 Conclusions

This chapter has demonstrated that it is possible to use BT in a industrial network The previous sections suggest a new approaches to improve the scheduling and the interference management in a BT network to industrial process control. In particular the following aspects are analyzed:

- In large industrial networks, multiple piconets can be deployed to work in parallel within a limited area. If they overlap, it is likely that a node transmission in a piconet will be affected by the co-channel interference due to the transmission, on the same channel and at the same time, of a node belonging to any of the co-located piconets. In this context, this paper analyzed the BT standard frequency hopping mechanism and observed that the frequencies in the hopping sequence do not recur before a certain number of hops. From this observation, a Piconet Management Approach has been defined, which aims to avoid (or, at least, to reduce) the interference between co-located BT piconets in industrial environments. The PMA allows a controller node to synchronize the clocks of the overlapping piconets and manage their frequencies, i.e. hopping sequences, to limit the interference between adjacent cells. This is accomplished introducing a variant in the standard frequency hopping algorithm which does not contrast with the operational modes defined in the BT standard. The results obtained through ns-2 simulations showed that the PMA achieves significant improvements in terms of collision reduction, thus leading to better network throughput, packet loss and delay.

- The new approach to real-time scheduling in BT networks proposed, called $M/S_{(EDF+CBS)}+S/S_{(EDF)}$, proved to be capable of increasing the amount of bandwidth available for both periodic and aperiodic transmissions. The approach also has the advantage of handling periodic and aperiodic traffic in an integrated fashion, while keeping periodic traffic isolated from aperiodic traffic. The use of real-time scheduling techniques, i.e. EDF and CBS, allows periodic traffic deadlines to be met in the various scenarios examined, while in the same conditions the standard BT approach experiences significant periodic packet loss and deadline miss values. The throughput and average delay for sporadic packets are also significantly better than those obtained by the standard approach. On-going work is dealing with the schedulability analysis of $M/S_{(EDF+CBS)}+S/S_{(EDF)}$, which corroborates the experimental evidence with analytical assessmnets on the schedulability enhancement enabled by the proposed approach.

Chapter 6

FINAL REMARKS

The use of wireless technology in industrial applications is very attractive, but introduces several problems, which have to be dealt with in order to fully exploit the advantages provided by wireless networks in automation.

Several works in the literature investigated the use of wireless technologies in industrial environments from different points of views, to solve specific problems or improve specific features. One major problem is the choice of a network architecture able to meet the typical industrial requirements.

This thesis proposed a two-tiered architecture as a viable solution for combining the stability, reliability and hard real-time support provided by wired networks with the flexibility, mobility support and soft real-time capabilities of wireless networks. To further extend the potential of two-tiered architectures, the thesis also proposes algorithms especially devised to solve specific problems in typical industrial scenarios.

The solutions presented in this thesis are based on the use of standard protocols, such as IEEE 802.11, IEEE 802.15.4 and Bluetooth, as they are widely available and accepted by customers. The proposed solutions have been analyzed through simulations to assess to what extent they improve the performance and real-time behaviour of the standard protocols.

With reference to the IEEE 802.11 protocol, a novel load-balancing algorithm able to dynamically compensate for fluctuations in the wireless link characteristics and in the load due to mobile nodes that join and leave the Access Point was proposed and analyzed in a typical industrial scenario. The results obtained are very promising and future work will deal with the extension of this mechanism so as to support both scheduled transmissions and contention-based transmissions (using EDCA).

As far as the IEEE 802.15.4 protocol is concerned, the design of a two-tiered network architecture for factory communication has been addressed. The thesis discusses the main challenges posed by the proposed architecture and how recent research results on the 802.15.4/ZigBee protocol can be exploited to deal with them.

Finally, the Bluetooth standard has been addressed and novel algorithms were proposed to improve its behaviour in industrial environments, with reference to a two-tiered industrial network. Two main issues were dealt with.

The first issue is the co-channel interference due to the transmission, on the same channel and at the same time, of nodes belonging to co-located piconets. The research started with the analysis of the BT standard frequency hopping mechanism. The analysis showed that the frequencies in the hopping sequence do not recur before a certain number of hops. Based on this result, a novel algorithm, called a Piconet Management Approach, was proposed, which aims to avoid (or, at least, to reduce) the interference between co-located BT piconets in industrial environments. The results showed that the PMA achieves significant improvements in terms of collision reduction, thus leading to better network throughput, packet loss and delay.

The second research issue relevant to BT networks dealt with in the thesis is transmission scheduling. A new approach to real-time scheduling in BT networks was proposed, that proved to be capable of increasing the amount of bandwidth available for both periodic and aperiodic transmissions. The use of real-time scheduling techniques allowed periodic traffic deadlines to be met in various industrial scenarios, while in the same operating conditions the standard BT approach experienced significant periodic packet losses and deadline misses.

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