



ROBOTS IN ASSISTED LIVING ENVIRONMENTS

UNOBTRUSIVE, EFFICIENT, RELIABLE AND
MODULAR SOLUTIONS FOR INDEPENDENT AGEING

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Abstract

Report document pertaining to the second phase of work conducted in the context of T3.3 regarding methods, designs, algorithms and techniques targeting network robustness and efficiency.

History and Contributors

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Executive Summary

Report documents on evaluations, methods, designs and developments concerning network communication reliability and performance.

Specifically, in chapter 2 a thorough hands-on experimental performance evaluation is presented considering prominent wireless ultra-low power communication technologies meaning to highlight pros and cons as well as suitability for RADIO scenarios.

Following this evaluation and taking into consideration potential weaknesses of Bluetooth Low energy networks when applied in RADIO scenarios a design is presented allowing multi-hop communication among nodes not supported by the default standard thus significantly enhancing respective capabilities.

From another perspective chapter 4 focused on the smart home infrastructure based on Z-Wave communication technologies and the enControl IoT platform highlighting approaches and methods concerning bridging respective network with the Robot.

Finally, chapter 5 focuses on the need for heterogeneous wireless communication technologies support and presents that complete design of a novel advances GateWay offering enhanced performance and behavioral features.

CONTENTS

Contents	iii
List of Figures	v
List of Tables	vi
1 Introduction.....	1
1.1 Purpose and Scope	1
1.2 Approach.....	1
1.3 Relation to other Work Packages and Deliverables	2
2 Performance Evaluation of Low Power Wireless Communication Technologies	3
2.1 IEEE 802.15.4 Based Solutions	3
2.1.1 Introduction.....	3
2.1.2 Performance Evaluation	4
2.2 Bluetooth Based Solutions	6
2.2.1 Introduction.....	6
2.2.2 Performance Evaluation	7
2.3 Bluetooth Low Energy Based Solutions	9
2.3.1 Introduction.....	9
2.3.2 Performance Evaluation	10
2.4 Summarization	11
3 Design of BLE Multi-Hop Communication Techniques	13
3.1 Current Trends	13
3.2 RADIO Solution	14
3.2.1 Network Formation	14
3.2.2 Message Forwarding	15
4 Smart Home – Robot Domain Bridging Techniques	17
4.1 Integration between the Platforms Smart Home and IoT.....	17
4.2 Integration between the Platforms Smart Home / IoT and Robot.....	17
4.3 Forthcoming Potential Functionalities	19
4.4 Benefits of an Integrated System	19
5 Advanced Gateway Design Supporting Heterogeneous Low Power Wireless Technologies	20
5.1 Introduction.....	20
5.2 Gateway Implementation Analysis	22
5.2.1 WSN Handler component	22
5.2.2 Message Broker component.....	23
5.2.3 Router Component	24



5.2.4	Scheduler component.....	24
5.2.5	Database component	25
5.2.6	Applications	26
References.....		27

LIST OF FIGURES

Figure 1: Relation to other Work Packages and Deliverables	2
Figure 2 IEEE 802.15.4 Mean Delay Performance with regards to Tx Nodes	4
Figure 3: IEEE 802.15.4 Mean Delay Performance with regards to Packet Payloads.....	5
Figure 4: Mean Throughput of CC2420 Testbed wrt No Security	5
Figure 5 Clock offset calculation procedure for Bluetooth based measurements	7
Figure 6: Mean Delay BT Performance	9
Figure 7: Mean Round Trip Delay BLE Performance	10
Figure 8: Advertisement/Scan Response packets' structure	14
Figure 9: Network discovery mechanism	15
Figure 10: Message Forwarding with broadcasting	16
Figure 11: Message Forwarding with selective broadcasting	16
Figure 12 Overall communication architecture between the RADIO Robot and the RADIO Home Platform	18
Figure 13 Conceptual Diagram of the GW Entity	21
Figure 14 Gateway Architecture	22
Figure 15 WSN Handler components	23
Figure 16 Messaging architecture	24
Figure 17 Gateway embedded database scheme	25



LIST OF TABLES

<i>Table 1. Wireless Sensor Communication Technologies Ranking</i>	<i>11</i>
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1 INTRODUCTION

1.1 Purpose and Scope

This deliverable is the final report describing the progress in Task 3.3 the main objective of which is to explore technologies, develop methods and design architectures pertaining to the network robustness and communication infrastructure efficiency upon which RADIO services can be based.

This deliverable aims to present different approaches and aspects explored by the consortium in order to strengthen network robustness and increase its efficiency.

1.2 Approach

The RADIO network infrastructure comprises various and diverse entities that need to collaborate so as to support the development of required services and wireless data transfer requirements. In that respect, in this final report the finalized developments are presented regarding:

- the Smart Home infrastructure offering efficient bridging techniques with the Robot,
- BLE based Wireless Sensor Network (WSN) offering support for heterogeneous ultra-low-power wireless communication techniques in the RADIO ecosystem, and
- a novel BLE gateway design offering reliable, robust and efficient performance, on one hand, controlling the WSN in all cases and, on the other hand, leveraging prominent technologies in order to yield back-end communication capabilities with the technician's UI, with the main controller and in any other component which may need to interact with the BLE RADIO network.

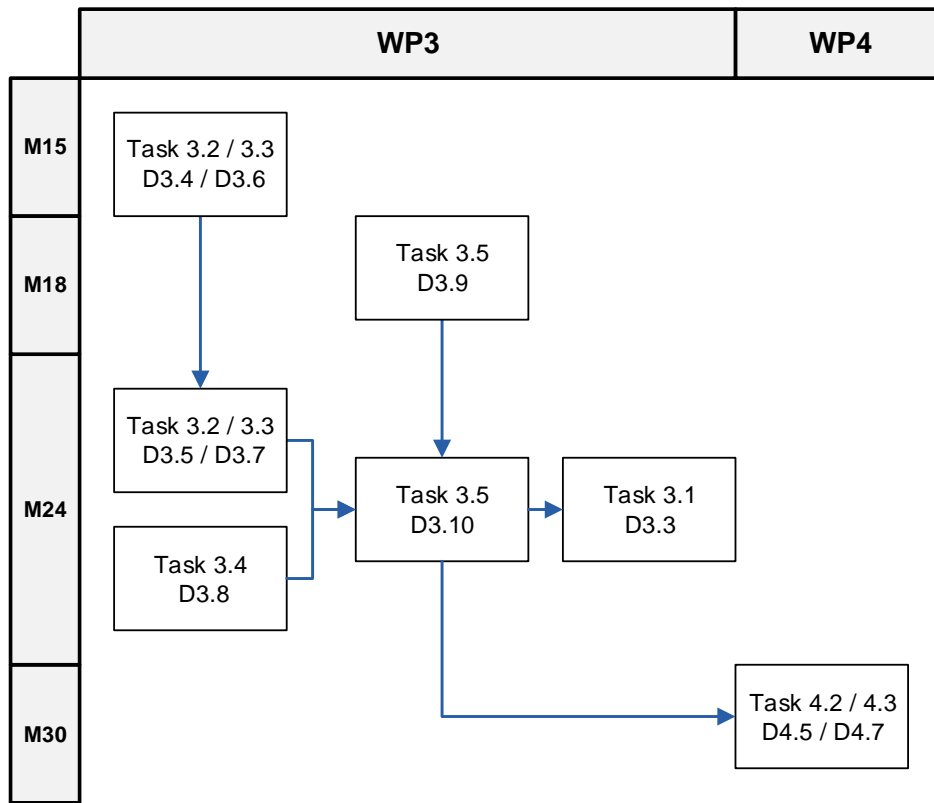


Figure 1: Relation to other Work Packages and Deliverables

1.3 Relation to other Work Packages and Deliverables

This document is part of a cluster of closely related deliverables. The initial *Network robustness and efficiency methods* (D3.6) are extended in this deliverable with the *communication, processing and security efficiency methods* relevant to the robot prototype (D4.6) and the mechanisms and protocols for the communication between the on-board components and the rest of the RADIO Home.

In this manner, work around ADL and Mood recognition is organized as follows:

- *Conceptual architecture II* (D3.2): Report, documenting the design and interconnections of the recognition components and used to guide development work.
- *ADL and mood recognition methods* (D3.4 and D3.5), *Network robustness and efficiency methods* (D3.6 and D3.7, this document), and *Social network analysis component* (D3.8): Reports, documenting the methods developed in order to recognize the activities and mood of the primary users. These reports are complemented by their open source prototypes found at the repositories indicated in each report and also collected in *Conceptual architecture* documents.
- *Integrated data analysis system* (D3.9, D3.10): Software, integrating the prototypes above into a coherent ADL/mood recognition system.
- *Conceptual architecture III* (D3.3): Report, documenting the final design and interconnections of the recognition components after changes and adjustments carried out during integration work.

These dependencies are also graphically depicted in Figure 1.

2 PERFORMANCE EVALUATION OF LOW POWER WIRELESS COMMUNICATION TECHNOLOGIES

Nowadays a plethora of short range, ultra-low power wireless communication technologies are available, all aiming to meet the requirements posed by home automation monitoring and control, event detection and even data streaming of relatively low bit rates. Therefore, in the context of home automation in RADIO as well as transmission of events created by ADL algorithms, a basic research has been undertaken aiming to evaluate the prominent examples of such technologies in a common set of scenarios so as to extract useful and practical conclusions with respect to the real requirements anticipated in RADIO scenarios. The set of technologies under evaluation comprise mature solutions integrated in wide range of commercial solutions targeting home automation application domain. The goal of this effort is mainly to extract and highlight respective pros and cons enabling the optimum selection of respective technology with respect to specific application scenario requirements both in the context of RADIO cases and beyond.

2.1 IEEE 802.15.4 Based Solutions

2.1.1 Introduction

Respective solutions comprise prominent candidates as they are utilized in several experimental and commercial scenarios. As the title implies, the communication capabilities are based on the IEEE 802.15.4 standard finalized by October 2003 [Part15.4]. Their popularity, gained throughout the years, is based on significant advantages when aiming towards very low power, low complexity, low price and low application demands characteristics.

At the physical layer, IEEE 802.15.4 offers three possible frequency ranges, although the most popular is the 2.4GHz ISM band where 16 channels can be utilized offering the highest bit rates equal to 250Kbps [Part15.4]. However, it is noted that at each particular time only one channel can be used, thus not being a multi-channel protocol.

Concerning the data transfer approaches, although the IEEE 802.15.4 defines approaches for both contention-less and contention based access schemes, the respective platforms implement and utilize only simple contention Carrier Sense Multiple Access (CSMA) based approaches. Following such an approach, all nodes are peers (i.e. there is no coordinator) and sense the transmission medium for two reasons. On one hand if a node wants to transmit a packet, it senses the medium until it is identified as idle and then transmits the packet. On the other hand, from the receiver perspective, a node senses the transmission medium in order to identify a packet transmission towards itself.

Popular IEEE 802.15.4 based platforms considered in this evaluation effort include TelosB and MicaZ. TelosB comprises probably the most well know WSN platform upon which many projects have been based including medical oriented ones [CodeBlue], [Shimmer]. As expected it offers an IEEE 802.15.4 compatible RF transceiver which can deliver 250Kbps bitrate at the 2.4GHz frequency band. Processing is based on the (also widely utilized) 8MHz Texas Instrument MSP430 16bit microprocessor. Concerning memory capabilities, the developer is provided with 48KB program flash, 10KB data ram and a 1MB external flash. It is noted that, although now TelosB is available through Memsic Co [Memsic], there are other platforms which although under different brand name offer identical characteristics such as [CM5000] and [Shimmer]. Shimmer is also a very interesting case since it offers a very versatile environment. A wide range of medical sensors can therefore be utilized extensively in this evaluation effort. MicaZ also comprises a prominent platform used in various scenarios and offering analogous characteristics as TelosB. The main difference concerns the processing module, which is based on an Atmel ATmega128L for both the radio and processing tasks offering 128KB program and 512KB data memory, while TelosB nodes are USB programmable and chargeable thus offering considerable higher usability compared to MicaZ where a separate programming module is required. It

is noted that products exist claiming higher bitrates [radio_pulse] for specific applications. Higher data rates (beyond the standard rates), often require custom solutions offering limited features. As far as software and network stack openness especially compared to the significantly more widely utilized, considering research objectives, platforms mentioned before. Therefore, they do not represent adequate solution for this evaluation.

2.1.2 Performance Evaluation

Undertaken evaluation focused on a typical scenario concerning a star topology comprised by one aggregating base-station node and variable number of reporting nodes. Additionally, the packet size also comprises a potential critical factor affecting the amount of information that a single packet can convey and the time period in which a wireless transmission medium is captured by a single transmitter. Finally, the most important system level performance metrics concern the rate of data the wireless medium can accommodate pertaining to the realistic capacity of the network and the mean packet delay pertaining to the time constrained communication capabilities of the network.

The evaluation results and their analyses are separated in two subsections, focused on the two performance aspects in CC2420 radio, delay and throughput. The first analyzed aspect is delay. Measurements presented in Figure 2 consider scenarios with and without security provision with a stable packet payload of 8 Bytes. As result, the relative effect of critical network parameters can be identified.

Focusing on the depicted graphs varying the number of transmitters (1,2,4), it is easily extracted, that the number of competing nodes comprises the most significant factor in IEEE 802.15.4 networks. Specifically, when no competition is developed (1 node communicating), the network exhibits low delays (around 10msec and never super passing) in all considered cases. On the contrary, increasing the competing nodes results in a delay increment to 25msec as packet creation interval for 2 nodes and even 100msec for 4 nodes. The highest delay measured also increases considerably in the 4 competing scenario reaching 23msec.

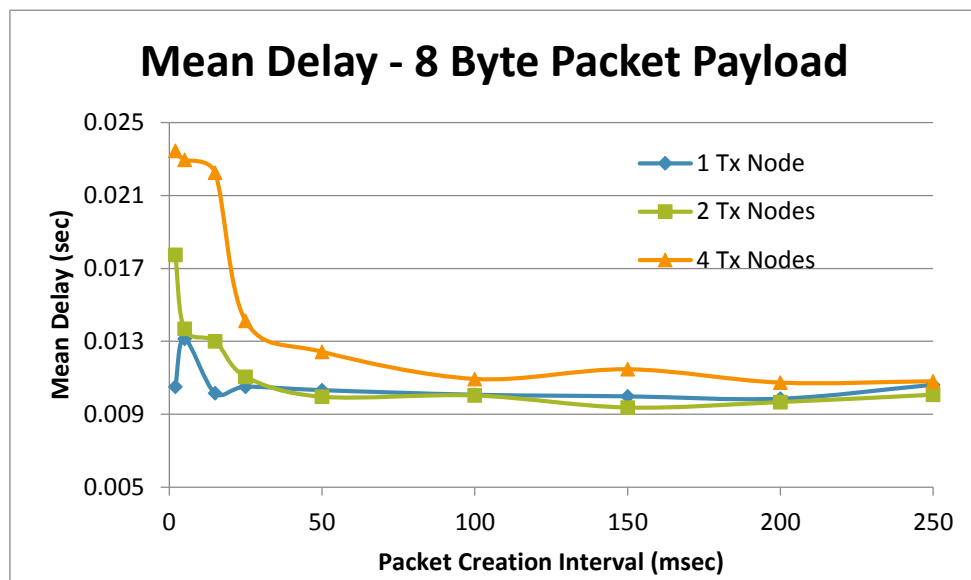


Figure 2 IEEE 802.15.4 Mean Delay Performance with regards to Tx Nodes

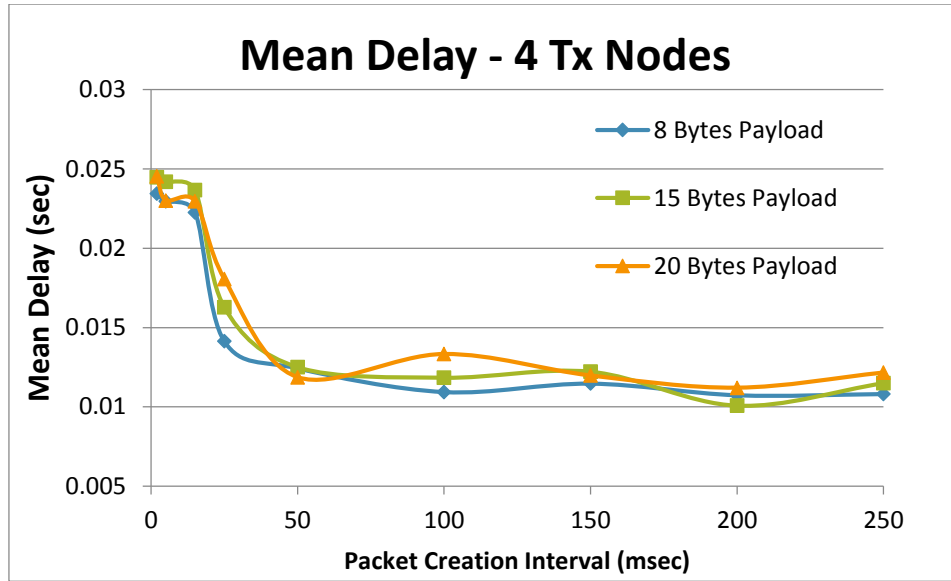


Figure 3: IEEE 802.15.4 Mean Delay Performance with regards to Packet Payloads

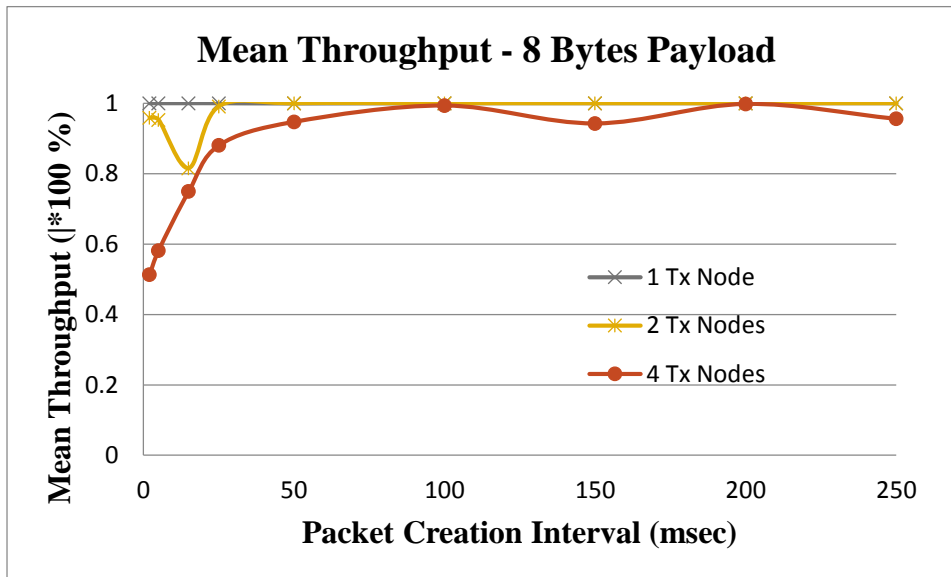


Figure 4: Mean Throughput of CC2420 Testbed wrt No Security

IEEE 802.15.4 offers significant flexibility and configurability as to the size of the packet defined by the user. Therefore, the next figure focuses on how network parameters and data payload affect the delay performance of the network in real CC2420 networks. In the following figures, the scenario represented is with 4 concurrent transmitting nodes and variable data payload size.

Different data payloads do not affect delay performance of the network when the competing nodes remain in relatively low but realistic numbers (i.e. 4 competing nodes) for typical scenarios. Therefore, in such cases using large packets is advocated in order to maximize the utilization of limited available bandwidth and if possible lower the required number of actual transmission for the same amount of data to be transmitted.

The second analyzed metric is throughput. As presented in the following figures, respective measurements concern the ratio of successfully received packets to the total number of packets transmitted. Figure 4, presents our measurements with a fixed packet payload of 8 Bytes.

Once again the number of competing nodes emerges as the most critical factor. With 1 competing node network we have 100% communication success. Increasing the competing nodes considered results in throughput degradation from 25msec packet creation interval for 2 nodes and even 100msec for 4 nodes. It is noted that when there are two competing nodes performance degradation does not always occurs since it is possible that the two nodes synchronize their transmissions through the CSMA Media Access Control (MAC) protocol in such a way that packets are not transmitted at exactly the same time. Effectively this is a statistical phenomenon not accurately quantified. Thus what is shown in Figure 3 is essentially mean valued of numerous repeated experiments. This is not the case in 4 transmitting nodes where performance degradation is always recorded as clearly indicated by the linear graph. The most severe degradation observation concerns 4 competing nodes, and 2 msec packet creation intervals, where mean throughput decreased to 51%. This result is quite discouraging for ARMOR related scenarios where multiple data flows will certainly coexist while transmitting in relatively high rates.

2.2 Bluetooth Based Solutions

2.2.1 Introduction

Bluetooth is a wireless radio specification designed to replace cables as the medium for data and voice signals between electronic devices. The specification is defined by the Bluetooth Special Interest Group (SIG) which is made up of over 1000 electronics manufacturers. Intended primarily for mobile devices, Bluetooth's design places a high priority on small size, low power consumption and low costs. The Bluetooth specification seeks to simplify communication between electronic devices by automating the connection process.

Bluetooth radios operate in the unlicensed 2.4GHz Industrial, Scientific, and Medical application (ISM) frequency range. This frequency is already widely used by devices such as microwave ovens, baby monitors, cordless telephones, and 802.11b/g wireless networking devices. In order to avoid interference from these devices, Bluetooth uses a technology called spread spectrum frequency hopping. Spread spectrum frequency hopping changes the transmission frequency up to 1600 times per second across 79 different frequencies. As a result, interference on any one of those frequencies will only last a fraction of a second. This, coupled with the limited range of Bluetooth radio transmitters, results in a robust signal that is highly tolerant of other devices sharing the same frequency.

Bluetooth devices automatically attempt to communicate whenever one device comes within the range of another. Bluetooth devices discover each other and initiate communication via inquiry and page transmissions.

Bluetooth devices have the ability to form ad hoc networks. The topology of these networks is both temporary and random. An ad hoc network of two or more Bluetooth devices is called a piconet. When two Bluetooth devices initiate a connection, they automatically determine if one device needs to control the other. Generally, the device that initiates the communication assumes the role of master and exercises certain controls over the other members of the piconet which are known as slaves. Upon establishing a piconet, the slave devices synchronize their frequency hopping sequence and system clock with that of the master in order to maintain their connection. A master device can have up to seven slaves. A slave in one piconet can also be the master in another, thus allowing piconets to overlap and interact forming what is known as a *scatternet*.

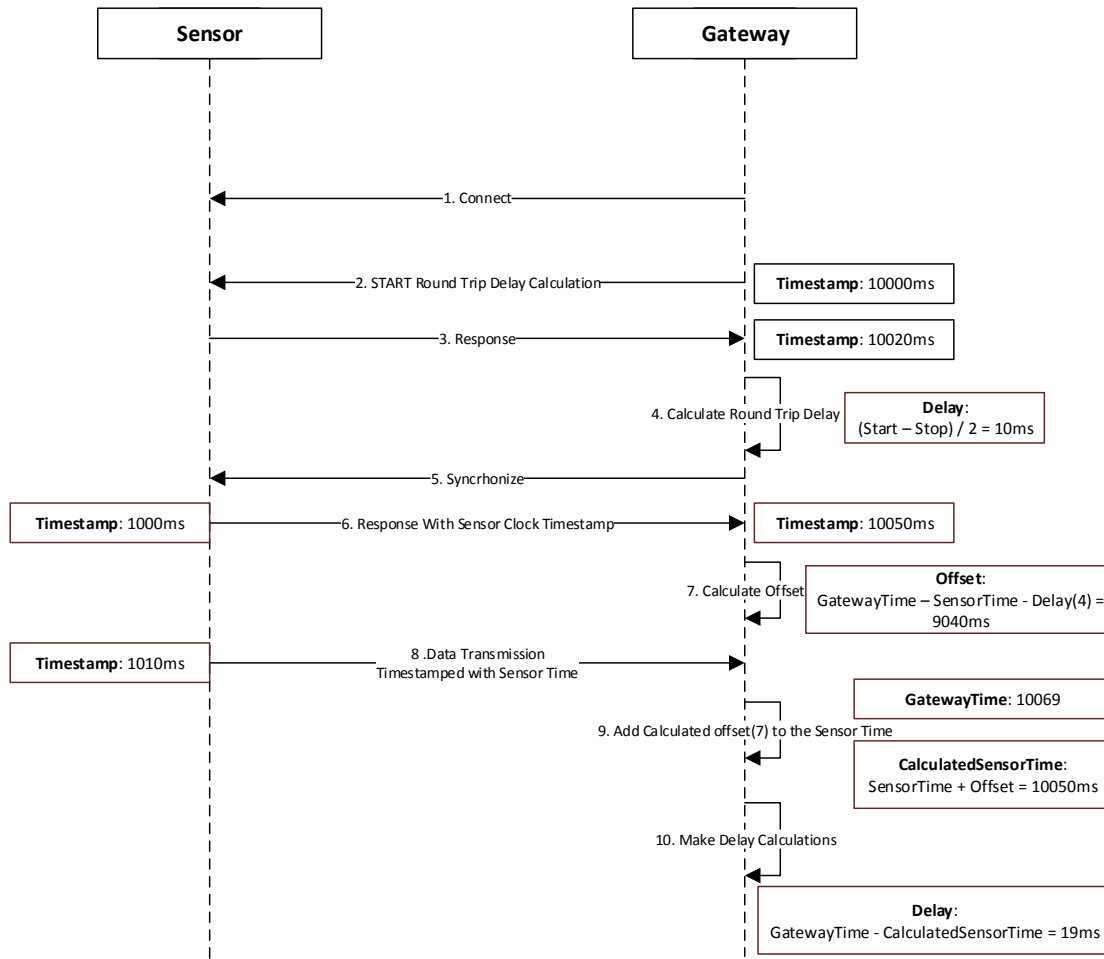


Figure 5 Clock offset calculation procedure for Bluetooth based measurements

Contrary to IEEE 802.15.4 based solutions where all relative platforms are characterized by analogous capabilities, the platforms in Bluetooth based solutions can vary significantly depending both on the version of the protocol supported and even more on the specific implementation's characteristics. Therefore, concerning data rates solutions covering a wide range from 300Kbps up to 1.5Mbps can be found. Indicative examples of relative solutions include Shimmer [Shimmer] and MoviSens [MoviSens] platforms. The former is utilized in the Roving Networks based Bluetooth modules [Roving2011].

2.2.2 Performance Evaluation

BT) communication performance, the Shimmer [Shimmer] platform was utilized offering a highly configurable environment and a standardized BT communication over the SPP (Serial Port Profile) service offering trouble-free compatibility with various BT receivers (both PC embedded and USB dongle). From the transmitter side, TinyOS based source code allows to configure the size of the payload and convey through that payload all required information to conduct the evaluation. On the transmitter side, an application has been developed allowing to easily conducting the association with the transmitter/s node/s and the parsing of data in order to make adequate calculations and extract respective measurements. In order to identify packet losses, each transmitter tags each generated packet with an increasing counter. In this way the receiver is able to check the sequence of the packet counter tags and identify any packet loss.

A significant issue that we had to address is how to accurately evaluate the effect on delay performance when both the transmitter and receiver have a completely different notion of time. In that respect before

data transmission commences, a specific packet exchange sequence has been designed and developed as depicted in Figure 5 enabling the calculation of the two clocks' offset thus enabling the accurate measuring of data packet delay. As depicted, after the sensor and the GW are connected the round trip delay is measured and the second exchange occurs (5 and 6 packets) so as to extract the clock offset. After this point, data transmission can commence and after each packet reception the offset is taken into consideration to counteract the clock difference.

Now moving on to the rest of the evaluation experiments, critical parameters considered are:

- Packet creation interval: 5-150msec
- Concurrent transmitters: 1,2,4,6 (7 being the maximum by BT requirements)
- Packet payload: 9, 20 Byte

Measurements Results

The first and of utmost importance observation extracted for respective measurements with respect to the document's objective concerns that in all scenarios there was a 100% success in packet transmission. It is shown that connection-oriented communication and FHSS transmission techniques offer significant advantages as far as communication robustness is concerned leading to no packet loss either with or without security provisions as well as while varying the packet payload. Such an observation emphatically advocates that the use of such technology is demanding application scenarios where highly sensitive data are handled.

Therefore, the evaluation results and their analysis focused on delay performance. In all graphs axis X indicates the inter-arrival time between consecutive packets in milliseconds. Y axis indicates the delay in milliseconds. Also "B" refers to the data payload and "Tr" refers to the number of nodes in the WSN. Figure 6 presents our measurements with varying packet payload.

It is easily extracted that the number of concurrent transmitting nodes on Bluetooth networks comprises the most significant factor affecting network delay performance. Specifically, when there is only one transmitting node the network exhibits very low delays, with a little differentiation even for quite stressed traffic workload conditions (i.e. 5msec packet creation interval) where the delay of successfully transmitted packets was approximately 20msec. These observations are extracted from both 9Byte and 20Byte packet payload scenarios.

What is more interesting is that even with a 15msec packet creation interval, configuration of the Bluetooth based network efficiently handled the created traffic from four competing nodes. This is depicted in Figure 6 when for the specific packet creation interval only a slight increase in packet delay is recorded. However, a quite emphatic delay deration is observed when a packet is created by the application layer every 5 sec. In this case and considering small packet size (i.e. 9Byte packet payload) delay more than doubles compared to 1 transmitter node scenarios reaching approximately 50msec. Furthermore it is in this case where packet payload size is highlighted as a critical factor. This is extracted from 20B, Tr6 graph where the mean delay spikes up to 190msec invalidating time constrained capabilities compared to all other graphs.

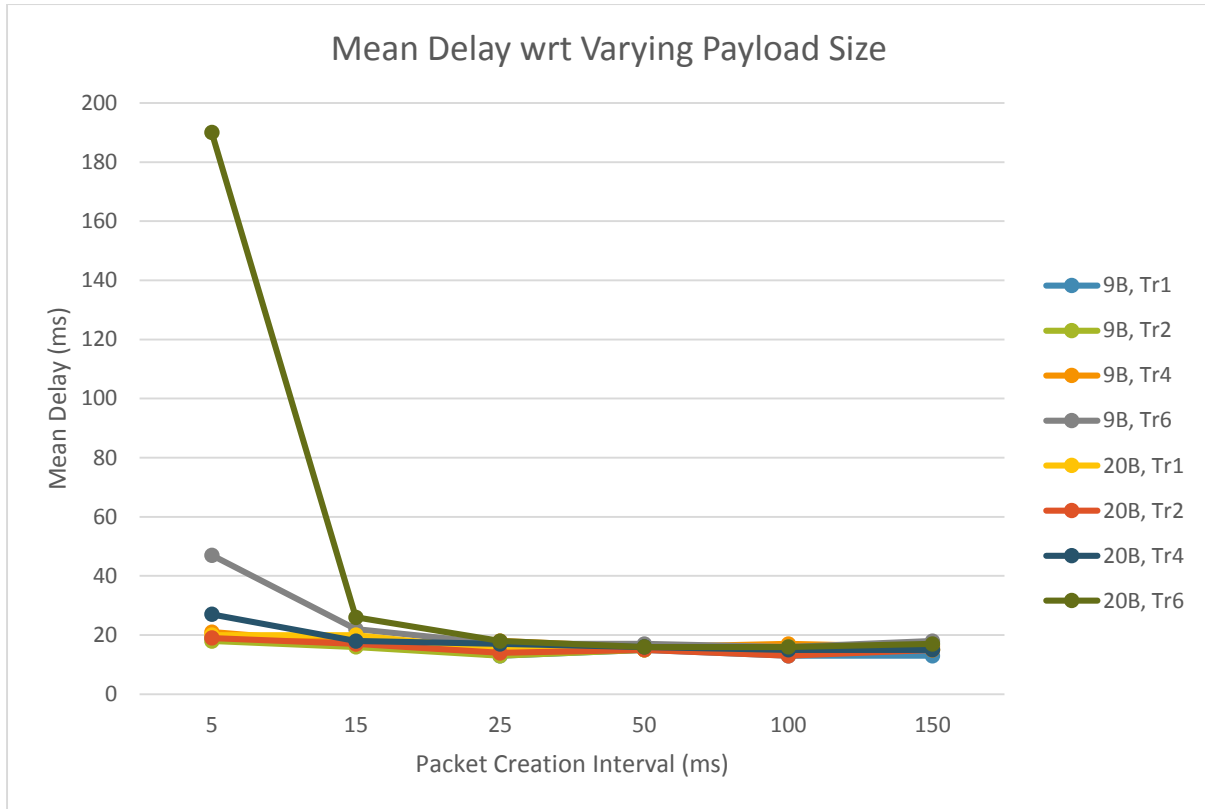


Figure 6: Mean Delay BT Performance

2.3 Bluetooth Low Energy Based Solutions

2.3.1 Introduction

Bluetooth Low Energy (BLE) represents a different technology from classic Bluetooth (and in fact incompatible technology) being promoted by the Bluetooth Special Interest Group (SIG) and benefitting of the hugely successful Classic Bluetooth it shows significant dynamics compared to analogous technologies being incorporated for example in most mobile devices such as smart phones and tablets, in high percentage of laptops and even in the latest version 3 of the also hugely successful Raspberry Pi. Furthermore, as presented in D4.1 (and omitted here for reasons of repetition avoidance) it offers high degree of flexibility both concerning implementation approaches and communication approaches supporting different ways for nodes to communicate through different data structure profiles so as to best fit the application requirements. Both these aspects are critical for the RADIO objectives highlighting relative solutions as good candidates for RADIO purposes. Also, being a protocol in progress regarding various aspects it also offers the added value of allowing the members of the RADIO consortium to be members of the Bluetooth SIG to gain valuable insight on future features of the standards and if possible even proposal respective approaches. However, the main fundamental step is to actually evaluate respective solutions and realistically and objectively verify that the performance offered is adequate for the goals of RADIO.

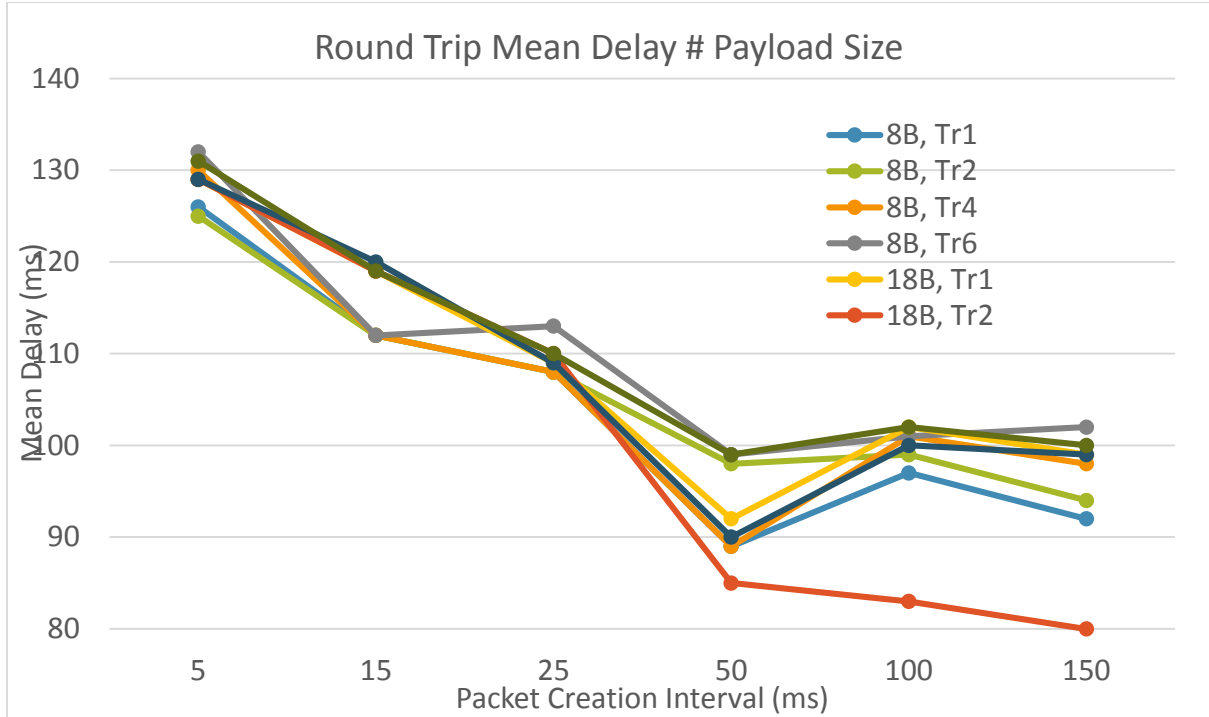


Figure 7: Mean Round Trip Delay BLE Performance

2.3.2 Performance Evaluation

In order to perform this fundamental performance evaluation we relied on the Sensor Tag [TI SensorTag] platform offered by Texas Instruments being a key player in BLE evolution. This platform comprises an ideal solution since it combines the best features from the commercial and research domain. With respect to the former aspect, relative platforms comprise very small nodes offering a wide range of sensors inside a robust case able to be used in real life scenarios. Concerning the research domain, relative nodes are programmable while the whole software stack is open source (offered by TI) allowing the development of custom solutions, possible extensions, enhancement and of course a way to test experimental ideas. In the context of aiming to test the communication capabilities under stressful scenarios, we created request-response sequences varying the request period while changing the number of nodes the gateway request data from. Specifically, considering as aggregation point a typical laptop equipped with a BLE USB dongle, the number of nodes towards which requests are issued range from 1 to 6 while the request periods range from 150msec down to 5msec (effectively representing a very stressed communication scenario). Finally, for reasons of completeness two packet payloads were considered (i.e. 8 and 18 Bytes) so as to explore the respective effect. Each evaluation session lasted the required time so as the gateway is able to send 5000 request towards each node. Focusing on the application layer performance metrics recorded concerned the number of responses received (and most importantly those that were not received) and of course the round trip delay measured by the aggregation point (i.e. the equivalent of the RADIO gateway according to the overall system architecture).

The first and very important observation concerns the exhibited communication robustness since there was no packet loss recorded. Every request was successfully responded in all cases and by all BLE nodes considered. Secondly as depicted in Figure 7 this robust behavior is accompanied by a quite predictable delay performance and respective effect of considered parameters. Based on the recorded performance, it can be safely deduced that the request period is the critical parameter to be considered. For low traffic scenarios (i.e. 150msec request period) the recorded round trip is measured (for all graphs apart 18B, Tr2) in range of 90-100msec corresponding to unidirectional delay of 45-50msec independently to the number of nodes comprising the network or the packet payload considered.

	IEEE 802.15.4	Bluetooth	BLE
Low Power	Very good	Good	Excellent
Link Capacity	Medium	Very Good	Very Good
Affected by communication competition	Medium	Very Good	Very Good
Multi-hop communication support	Excellent	Medium	Very Good
Dynamic Topology	Excellent	Medium	Very Good
Time constrained performance adequate for RADIO	Yes	Yes	Yes
Low Cost	Very Good	Good	Excellent
Market Widespread	Medium	Excellent	Excellent

Table 1. Wireless Sensor Communication Technologies Ranking

The second observation to be made concerns the request period equal to 25msec since it seems that these point on (i.e. for lower request periods corresponding the scenarios of increasing stress workload) a clearly leaner mean delay increase indicating a network moving towards congestion situations. However, even in the most stressed cases considered (clearly surpassing what is anticipated to be encountered in typical RADIO scenarios) the BLE network did not reach congestion since no packet loss and a measurable but relative low delay overhead is recorded. Specifically, as it can be observed maximum recorded round trip delay is in the range of 125-131msec roughly corresponding to a unidirectional delay of ~64msec easily covering any real time requirements posed by the RADIO application scenarios.

2.4 Summarization

Nowadays and most probably in the future there will be a variety of different and diverse communication technologies claiming a part of the short range, ultra-low power, and wireless communication market. In this section a basic evaluation research is presented aiming to evaluate suitability with respect to the RADIO communication requirements and to reveal specific characteristics as well as pros and cons. Such insights are very important because we envision the RADIO platform as a continuously evolving system much beyond the RADIO project timeframe and in order to assure the extended lifetime of the developed framework it must be able to embrace and integrate current as well as new technologies. What is clear from studying the considered technologies both at literature level but most importantly by hands on experience and by putting them under a variety of tests is that each offers unique characteristics distinguishing each solution from the other and making each technology a better fit compared to the others considering different communication requirements both functional as well as non-functional. Therefore, we present a table of characteristics most relative to the RADIO communication aspects and we attempt to rank considered technologies.

From Table 1 it can be deduced that all the available solutions should be seen as competitive technologies but more as complementary solutions each on offering specific advantages to specific application scenarios and requirements. In that respect in RADIO aiming to offer highly efficient and

robust communication solution and infrastructure, a critical goal will be to design and develop a novel Gateway component. The main focus is on enabling integration of all prominent heterogeneous technologies thus promoting cooperative communication and data transfer. Respective solutions will be presented in following section of this deliverable and a primary concern will be the seamless cooperation with commercial solutions offered in the RADIO project.

3 DESIGN OF BLE MULTI-HOP COMMUNICATION TECHNIQUES

Bluetooth Low Energy (BLE) has attracted significant interest due to its inherent characteristics as briefly described in Chapter 2. The increased adoption of the BLE technologies in the IoT domain has enabled researchers, companies and the Bluetooth Special Interest Group (SIG) to explore the feasibility of mesh networking over BLE. Currently, enhancements focused on mesh networking are on the roadmap of all the BLE related vendors. BLE mesh support is expected to provide new capabilities and increase the IoT functionalities.

3.1 Current Trends

Dominant players in the market of low power wireless SoCs and BLE particularly, have already released their first efforts towards mesh enabled BLE networks. Since the standardization of a mesh mechanism for BLE has not been finalized yet, each company is working on its own version of mesh networking over Bluetooth.

CSR enables mesh networking through a proposed CSRmesh service layer [CSRmesh]. CSRmesh nodes receive advertisement messages and broadcast them to the surrounding devices with maintaining any routing table. Through this flooding mechanism, packets are propagated through the network of the BLE devices and thus, a simple ad-hoc mesh network is formed for the IoT application domain. The first large scale deployments of CSRmesh are applied in buildings with smart LED lighting fixtures and are controlled through Android and iOS devices. Details on CSRMesh are given later in the chapter where some primary performance evaluation is performed.

Nordic Semiconductors is another chipmaker that provides its version of mesh networking on its Bluetooth smart devices through the nRF OpenMesh framework [OpenMesh]. nRF OpenMesh is similar to the CSRmesh message rebroadcasting infrastructure. The message propagation is controlled by *Trickle*, a flood control algorithm for lossy low power networks [Levis, 2011].

Another popular vendor on the wireless communication SoCs, the Dialog semiconductors, released the Smartbond DA14680 SoC family that is able to run the OpenThread [OpenThread] which is the open-source implementation of the Thread [Thread] networking protocol. Through the OpenThread Sandbox development kit, developers are able to establish mesh networking and evaluate the protocol stack's performance.

Finally, Texas Instrument (TI) has released the prominent CC26XX SoC family that provides BLE connectivity. Though TI doesn't distribute its SoC with a custom version of a mesh networking, developers can take advantage of the SoCs' BLE 4.1 support and define their custom BLE mesh network with CC26XX using Advertising & Scanning

So far, each vendor provides its own approach on BLE mesh networking as already identified. In the meantime, the SIG has been focused on the standardization of mesh networking in order to include this standard into the Bluetooth specification. The main objective of the Bluetooth SIG through the respective working group is to allow mesh networking capability in the standard and add to the Bluetooth certified devices mesh networking functionality. As Bluetooth Smart sensors mainly target smart home applications, mesh networking aims to become an integral component in order to deliver Bluetooth-enabled smart locks, lights, Heating, Ventilation, and Air Conditioning (HVAC) systems, and cooperation among appliances.

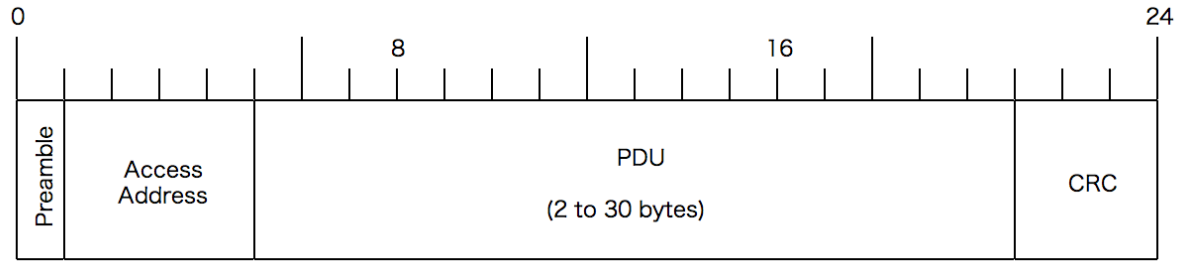


Figure 8: Advertisement/Scan Response packets' structure

The *Bluetooth Smart Mesh Working Group*, which is involved in the respective project, is supported voluntarily by over eighty member companies from a broad spectrum of industries, including automotive, mobile phone/mobility, industrial automation, home automation, consumer electronics, and computing. The Bluetooth SIG published on December 2016 the Bluetooth 5 with significant advances over Bluetooth 4.x (2x bandwidth, 4x the range, 8x broadcasting capacity compared to the Bluetooth 4.2) but Bluetooth Mesh was not part of this release and is expected in the first half of 2017.

3.2 RADIO Solution

The RADIO project identifies the popularity that BLE attracts and foresees the benefits that modern IoT and Ambient Assisted Living (AAL) application domains will gain from the upcoming BLE mesh networking support. Therefore, RADIO designs a mesh mechanism that will be integrated in distributed sensor/actuator devices scattered across the RADIO AAL environment.

3.2.1 Network Formation

After a thorough study of the existing approaches, the RADIO BLE mesh networking mechanism focused on the principles of BLE connectionless communications through advertising and scanning.

Advertising is the act of broadcasting data and it aims in device discovery and data publishing. The advertising mechanism involves 2 possible types of data packets that can be transmitted. The mandatory packet is the advertising packet while a node can optionally send a Scan Response packet. These two types of packets are structured mainly by the advertiser address and 31 bytes of payload as presented in Figure 8. During the normal operation, the BLE advertiser constantly broadcasts the advertising packets within an advertising interval bounded by a minimum and maximum value. These intervals typically may range from 20ms to 10.24s.

During the network formation phase, the RADIO mesh mechanism utilize the advertisement packets along with the broadcasting technique in order to achieve the network formation and route discovery. During the initialization of the network, each node broadcasts an advertising packet, which is the route discovery packet (route request - RREQ) in the context of the RADIO mesh. The RREQ messages are forwarded by each adjacent node until a pair of nodes exchange RREQs. Then a RREP message which contains the repliers address is sent backwards. During the reception of the RREPs, the respective neighbors table of each node is built. An instance of the neighbors' table construction is presented in Figure 8.

This flooding approach replicates every message at every relay node and it delivers near optimal delivery probability. Furthermore, it doesn't require any knowledge about the network during the design time. The increased resource consumption can be tolerated since flooding occurs once during the network initialization. Furthermore, the deployment scale of the RADIO mesh network is not expected to expand more than a few nodes for a small to medium network size. Scalability is accomplished since the route discovery can be performed on a new node's entrance.

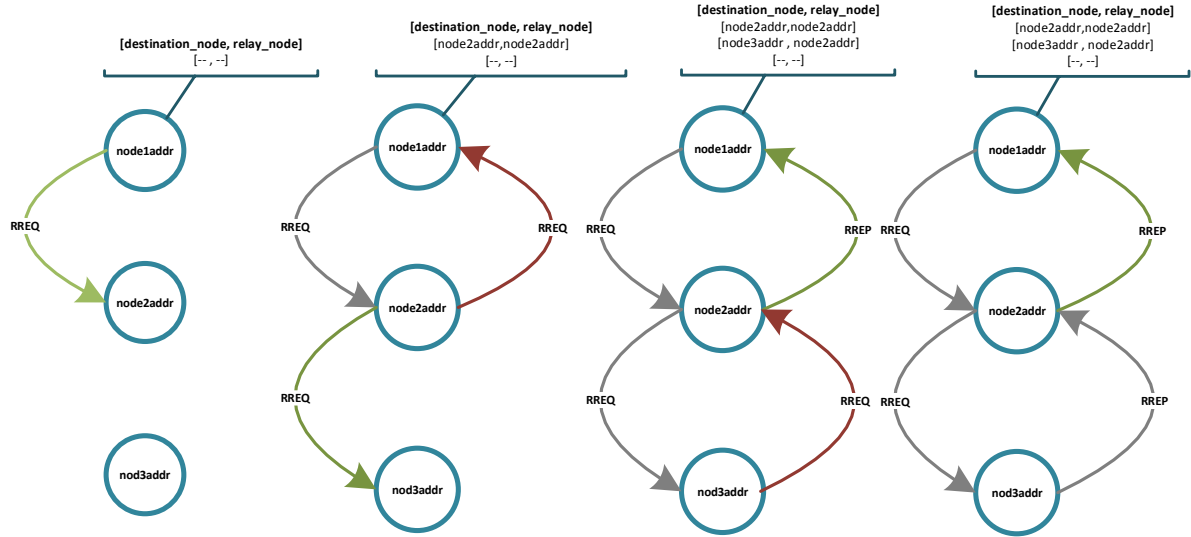


Figure 9: Network discovery mechanism

3.2.2 Message Forwarding

After the network discovery is completed by every node of the network every node has knowledge about its surrounding neighbors. The nodes now are ready to start forwarding their data messages. The approach followed in every version of BLE mesh released by the industry so far as on the connectionless mode of BLE and advertisements are used as data carriers.

The first approach of the RADIO mesh forwards data messages through rebroadcasting. Rebroadcasting works by flooding all messages to all nodes in the network through broadcasts. Nodes are in scanning mode and when an advertisement is received, the receiver rebroadcasts it to its neighbors (Figure 9). The process is repeated on every node and it is completed when every node receives the respective message. To avoid the broadcast storms through the continuously rebroadcasting of the same message, a versioning mechanism is implemented and runs on every receiver node. Upon the generation of the message on the source node, a version indicator is paired with the respective value and propagated along the network. Each relay node that receives the message stores it in a local data table. On every reception of a message from the same source and sensor, the relay node checks the version of the packet and propagates it to its neighbors if the received message version differs from the local. The message broadcasting process is completed when every node in the network received the message.

While broadcasting may increase the packet delivery ratio due to route redundancy has a major drawback which highly affects the network performance under various network traffic loads and node density. Bluetooth Smart uses 40 RF channels in the ISM band (2.4GHz). These RF channels have center frequencies $2402 + k \cdot 2\text{MHz}$ where k ranges from 0 to 39. Advertising utilizes three of them specifically channel 37 (2402MHz), 38 (2426MHz) and 39 (2480MHz). Due to broadcasting, the network is flooded with redundant transmissions. Thus, the poor utilization of frequency bands may degrade network performance and overall power consumption.

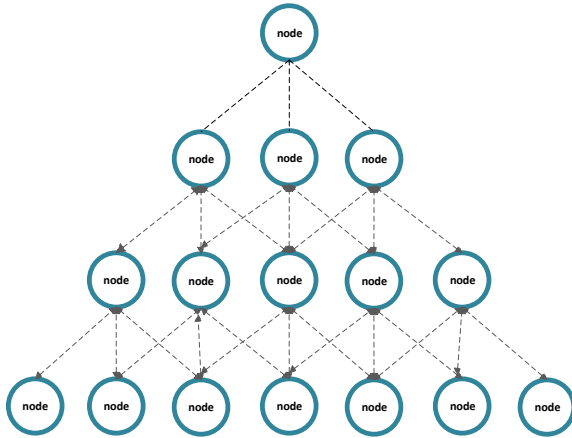


Figure 10: Message Forwarding with broadcasting

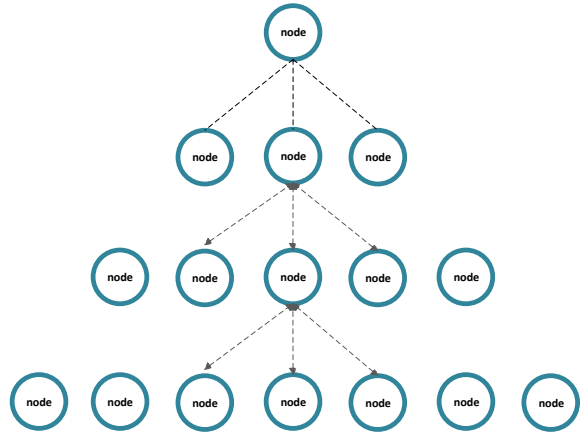


Figure 11: Message Forwarding with selective broadcasting

During the development and evaluation phase of the RADIO mesh a selective broadcasting policy was implemented. As described earlier, during the network phase, the nodes discover their neighbors and they store this knowledge locally. This knowledge is used to build the respective forwarding mechanism depending on the destination of their transmissions. These routing tables are used by the RADIO mesh to perform the selective broadcasting mechanism. The 29 bytes of payload are used to encapsulate the address of the destination node, the sensor model (described by the data type and data value) and the message version (described later). The application domain where RADIO mesh will be deployed handles simple numeric sensor values that do not demand large packet payloads to carry them through the network. Therefore, the 29 bytes of the BLE advertisement packet is considered adequate for similar applications.

During the operation of the RADIO mesh with the selective broadcast enabled, every parent node that receives a message by the child node parses the payload of the packet and checks the packet's destination node. If the destination node is registered in its routing table, the message is rebroadcasted to its neighbors. In case the relay node doesn't retrieve a route to the destination node it discards the packet from its queue. Figure 10 and Figure 11 give a visual representation of the traffic generated by the broadcasting and selective broadcasting transmissions. The figures show how the traffic load differentiates among the two approaches. Particularly we observe that selective broadcast relaxes the traffic load significantly, while at the same time retains a degree of route redundancy that benefits the packet delivery ratio without abusing the network resources.

4 SMART HOME – ROBOT DOMAIN BRIDGING TECHNIQUES

In the context of RADIO, the smart home service and the robot service are integrated into a unique solution. The data communication between the smart home and the robot will be done through the smart home controller or the IoT platform by using a client-server technology. The client system requests services provided by the server.

As designed in Deliverable 5.1, the components of the RADIO ecosystem are the smart home platform, IoT platform, and the robot platform. The smart home platform contains sensors and actuators deployed in the home location and the smart home controller (SHC). The IoT platform is a collection of smart home services outside the boundaries of the smart home that aims to provide more complex automation functionality, such as the request of historical data by the robot. Finally, the robot is responsible of monitoring and assisting patients in carrying out activities of daily living.

4.1 Integration between the Platforms Smart Home and IoT

The integration between the Smart Home platform and the IoT platform was already developed in order to provide the following services:

1. Remote management of the sensors and actuators: upload/download sensor values, upload/download sensor and actuators status, and download sensor firmware. The SHC is responsible of (i) acquiring data from sensors by using communication protocols such as WiFi, Z-Wave (ii) storing the last state/values from the sensors and actuators, and (iii) sending this information to the IoT platform to be stored as historical data when new information arrives. The sensor information transmitted and stored in the SHC is the name, the specific location of the sensor inside the home, the type (magnet, presence, thermostat, etc.), the value measured, and the current status.
2. Management of the data generated by the sensors.
3. Real-time event communication between the IoT platform and the smart home: This event service API relies on ASP.NET SignalR technology that provides real-time web functionality in order to support a “server push” feature. The model of communication between clients and servers supported by the SignalR API and implemented in the RADIO context is the Hubs communication model.
4. Secure communication: Standard security mechanisms such as authentication mechanisms, self-signed certificates and HTTPS protocols have been developed.

A more detailed description of the integration between these platforms was given in Chapter 6 of Deliverable 5.1. The source code of the Java API and C# API can be found as an annex to D5.1 [RADIO D5.1].

4.2 Integration between the Platforms Smart Home / IoT and Robot

The integration between the smart home, the IoT platform and the robot platform enables the addition of new functionalities to the RADIO ecosystem. Mainly, the robot will be able to ask for information about the smart home in order to:

- Gain new insights about the status of the patient.
- Carry out some specific action by itself in order to ensure patient safety.
- Perform changes by using the actuators (switch on/off smart plugs, switch on/off lights, dimming of lights, thermostat target temperature, open/close doors, shadows, curtains, etc.) to ensure patient comfort. This task will require that the robot sends a command to the SHC, i.e. the robot will act as a server

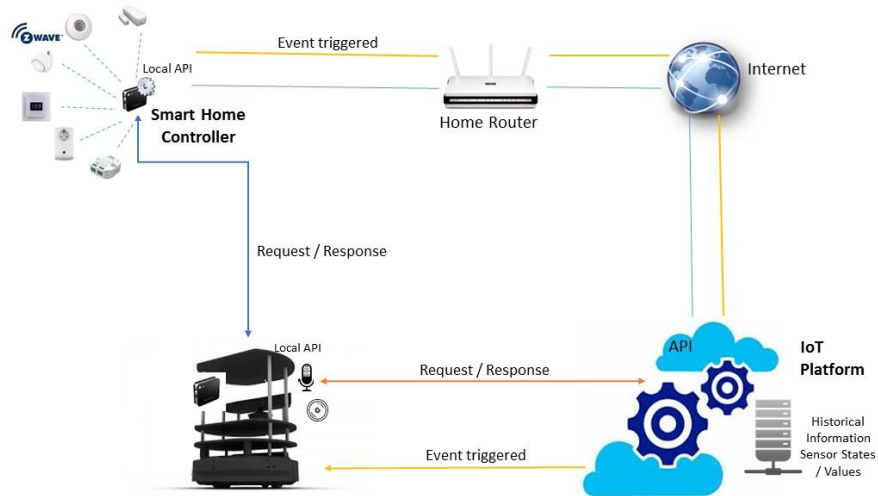


Figure 12 Overall communication architecture between the RADIO Robot and the RADIO Home Platform

The further integration between the platforms smart home and robot requires the development of new communication protocols based on the robot's tasks:

1. **Polling protocol:** The robot acts as a client polling the SHC for information that, in turn, sends its data only in response to the poll request. This can happen when the robot needs information about the home status on a regular basis to complete information about the status of the patient. The SHC acts as a server in this situation.
2. **Real time event-triggered:** An anomaly is detected by the SHC (or the IoT platform) and the information or a specific trigger is sent to the robot to take some specific action. The SHC acts as a server in this case.
3. **Request of historical data:** In this case, the IoT platform acts as a server. Since it is highly desirable not to drain the battery of the robot in this case, a number of query optimisation methods of data selection and data aggregation are available in order to decrease the amount of exchanged information between the robot and the IoT platform. Less information to be transmitted will imply less time to be devoted to this task and, therefore, battery power saving. The database optimisation techniques are
 - Data selection: A filtering algorithm is used to select a subset of the data. The robot can ask for specific information by using the sensor type or a date range.
 - Data aggregation: This protocol allows replacing groups of values with summary statistics based on those values. In particular, data can be merged by the sum or arithmetical mean of all aggregated values. These data aggregation techniques were developed in a big data and cloud environment. Further information is provided by task 4.2 'Embedded device design and development'.

Figure 11 shows the communication architecture between the RADIO home platform and RADIO robot.

The overall communication relies on a strong collaboration between the smart home and robot developers in order to use robust and efficient APIs and to define new data aggregation techniques for optimal information extraction.

4.3 Forthcoming Potential Functionalities

As mentioned earlier, the development of this overall integration within the RADIO context will provide a number of potential functionalities such as:

- To recognise and assist a wider number of ADLs by using smart home information.
- To combine data acquired from both platforms. The robot platform will detect activity patterns that will be complemented with data coming from the smart home platform capable of modelling user behaviour based on household energy consumption data.
- To explore the correlation between the household energy consumption data and a user's wellness. The household energy consumption pattern anomalies represent changes in user behaviour.
- To increase the robot's functionalities, e.g. allowing the control of the smart home actuators by the robot.
- To improve the smart home's functionalities by using data acquired by the robot, e.g. improving the smart lighting system by knowing the indoor position of the patient.

4.4 Benefits of an Integrated System

An integrated system promotes efficiency and reduces costs in terms of:

- Facilitating the management of the sub-systems from a unique service.
- Improving response time.
- Data collected by different systems lead to better decision making.

A unified data model reduces the complexity of matching, cleaning and preparing all data for different applications.

5 ADVANCED GATEWAY DESIGN SUPPORTING HETEROGENEOUS LOW POWER WIRELESS TECHNOLOGIES

5.1 Introduction

Envisioning RADIO as a continuously evolving, flexible Cyber Physical System (CPS) platform, regarding the communication perspective, typically, short range wireless communication protocols enable data aggregation to a central point (indicated as the Gateway). Although a plethora of different communication technologies (mainly originating from WSN research domain) are available, they offer diverse characteristics exhibiting high degree of incompatibility. In that respect a highly efficient gateway design has been designed and explored in the context of RADIO able to support the most prominent short range wireless communication technologies such as IEEE 802.15.4 [802.15.4 Spec], ZigBee [ZigBee], Bluetooth [Bluetooth], BLE [BLE] and Z-Wave [ZWave]. Also, a critical goal of the design is to facilitate the continuous development and integration of new solutions. Communication complexity however, is also related to efficient data transfer between the gateway and remote installations like service providers, databases, graphical user interfaces etc. Consequently, the presented gateway design supports both HTTP based communication facilitating well-known technologies such as REST, SOAP as well as more contemporary approaches such as message passing communication aiming to support increased communication complexity.

Furthermore, the increased functional complexity calls for new processing capabilities in the future gateway designs. In order to address the respective challenge, the explored Gateway design highlights the ability to support data acquisition by different modalities and using different communication technologies to be synchronized, homogenized and processed. In this way, sophisticated load balancing, data merging, QoS, prioritizing and many more mechanisms can be supported. This approach also facilitates real-time data processing and event detection which is of paramount importance in demanding applications such as medical and industrial deployments.

The RADIO platform intends to be a continuously evolving solution that is able to cover major CPS including end-to-end data communication, processing, storage and representation requirements. In this context and focusing on the RADIO home automation environment, starting from the left hand side of Figure 13, an efficient, flexible and extendible approach is targeted so that any kind of heterogeneous sensor or actuation modality is aggregated at the proposed gateway. A critical goal here is to support heterogeneous technologies in a homogeneous way regardless of being connection or connectionless oriented, supporting or not supporting multi-hop packet transmission, supporting QoS mechanisms or not, offering high throughput capabilities or not etc. Then, the next important conceptual design choice concerns the way data, events or/and commands can be exchanged between the gateway and the backend infrastructure (i.e. the RADIO IoT platform). Once again, the main goal is to focus on maximum flexibility and extendibility so as both complex modalities and complex applications can be addressed. Consequently, apart from the typical HTTP APIs, a message passing API is also supported and provided. Based on these APIs, the developer can design and implement services tailored to the needs of specific applications.

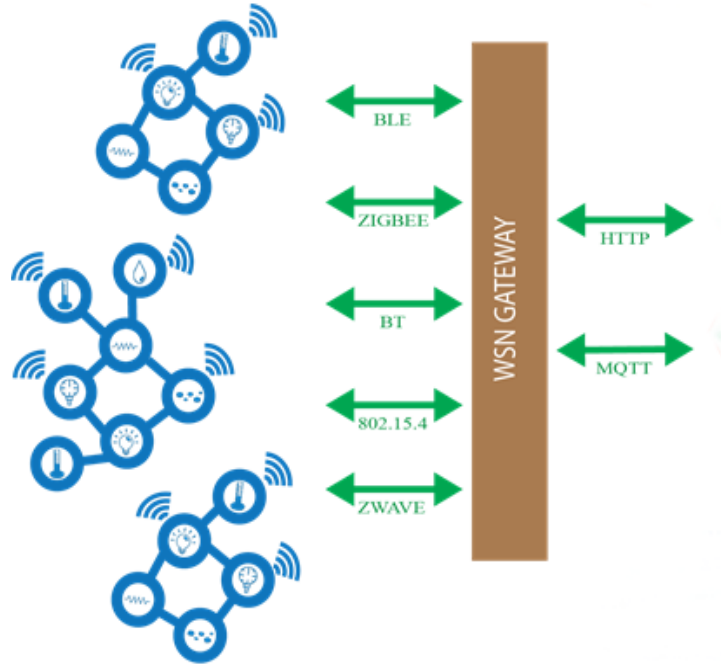


Figure 13 Conceptual Diagram of the GW Entity

In the context of the presented implementation, WSN sensors communicate through technologies such as Bluetooth and ZigBee, using the MQTT-SN [MQTT-SN] protocol, and connect with the Gateway in order to communicate with the IP network, as well as interacting with sensors based on different wireless communication technologies. The gateway is an intermediate component where data are collected and processed before being forwarded to the core network for further processing.

In most monitoring WSNs development and deployment, one of the most vital goals is to collect and aggregate the sensor data (e.g., environmental data, patient data, battlefield data) for analysis. To this end, the development of a WSN gateway is critical for data gathering by diverse WSNs in real-world scenarios. The focus is to design and implement a fully user-configurable WSN gateway architecture for effective and efficient data collection; this will enable easy integration of different WSNs applications to the gateway and adhering to different communication technologies. The WSN gateway will be able to parse and analyze dynamic packet formats with variable packet sizes. Many message passing protocols [AMQP], [STOMP], [Banks 2014] have been created over the years, but a simple and lightweight protocol is needed. In that respect, MQTT-SN, has been selected as the preferred communication protocol in order to support communication heterogeneity in WSN, with dynamic packet formats in a homogeneous manner. MQTT-SN is a publish/subscribe messaging protocol that extends the well-established *Message Queue Telemetry Transport (MQTT)* protocol in order to cope with the specific constraints of WSNs, such as resource-limited and battery-operated devices, low network bandwidth and high link failures. It provides an intuitive application programming interface that hides completely the complexity of the underlying networking technologies. MQTT-SN is a highly developed protocol, and the one with the most standardization attempts for WSNs [Robinson, 2005]; it has been widely used for remote monitoring applications [Ullas, 2014], messaging applications and a range of home automation applications [Erratt, 2013].

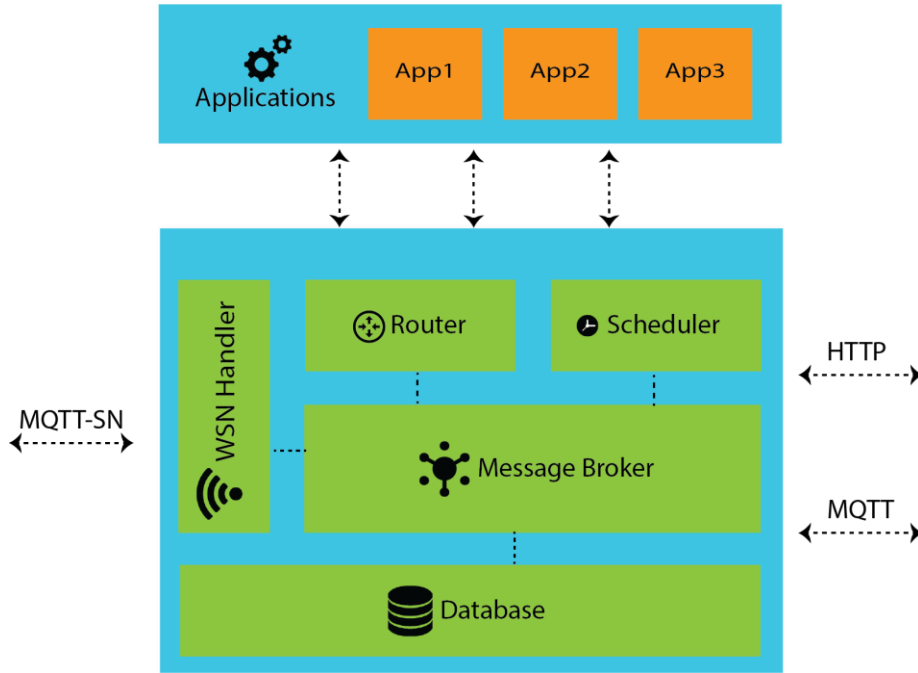


Figure 14 Gateway Architecture

5.2 Gateway Implementation Analysis

The gateway is the main aggregation point for the data collected from sensors in the physical environment, which makes it a fundamental component for the network. The core gateway implementation has been written in JAVA programming language, using the Spring [Spring] framework, in order to provide component-based architecture and auto wiring functionality to the gateway kernel. A high level architecture of the gateway is depicted in Figure 14.

At the top level of the architecture, all user-defined applications that will run in the gateway are placed. An example of such application is a monitoring application for the lights of a house. Moving towards lower layers of the software stack, the proposed gateway defines networking and storage modules for handling communication and storage requirements respectively, as well as orchestrators that used to join all these components together.

5.2.1 WSN Handler component

The WSN handler component initializes, maintains and destroys connections with the Wireless Sensor Network. In order to handle the heterogeneity of the underlying network, it is divided in several sub-components, with each one handling different aspects of the network. In the context of the RADIO project, the main responsibility is to maintain connections for the BLE wireless technology, for both connection-based and connection-less devices, as well as sending advertisements to the network. As shown in Figure 15, there are three main subcomponents in order to handle the BLE network, namely Advertisements Publisher, Advertisements Scanner and GATT Handler.

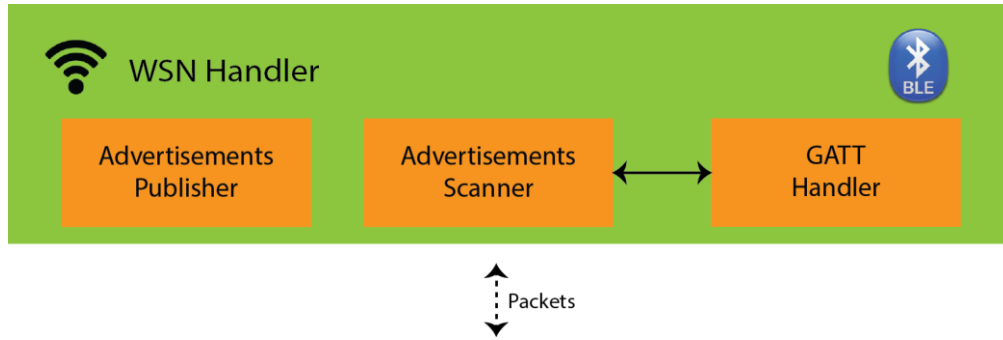


Figure 15 WSN Handler components

The *Advertisements publisher* is responsible to publish messages, originated from the gateway, to the BLE network, while the *Advertisements scanner* is the main aggregation point for all advertisements types originated from the BLE network. When a new advertisement arrived at the Advertisements scanner, it checks if the advertisements come from a known device, and then determines the advertisement type from the BLE PDU. There are many types of advertisements according to the Bluetooth Specification [BLE]. In the context of the RADIO project the types of advertisements that are of interest are:

1. ADV_NONCONN_IND, Non connectable undirected advertising. Used by devices that want to broadcast and don't want to be connected or scannable. This is the only option for a device that is only a transmitter.
2. ADV_DIRECT_IND, Connectable directed advertising. Directed advertising is used when a device needs to connect to another device.

For the *ADV_NONCONN_IND* advertisements, when the scanner received this type of advertisement just forwarding it to the corresponding components of the Gateway. In contrast, when receiving an *ADV_DIRECT_IND* advertisement, it forwards it to the GATT handler, which in turn, is responsible to initialize a new connection with the device, configure all the parameters in order to collect data and finally, if needed, to close the connection with the sensor device. The GATT handler contains all the necessary functionalities in order to forward the collected data to the appropriate consumers.

5.2.2 Message Broker component

The gateway embedded broker expose messaging capabilities to the gateway, which offers communication flexibility between the gateway core components and applications, running or not on the same operating system with the gateway. The embedded broker is based on ActiveMQ [ActiveMQ] broker (core) along with some additional plugins for communication and authentication capabilities. For the gateway core components the message broker exposes a *vm* connection (Java Virtual Machine connection), and for the applications that are not part of the core gateway the message broker exposes a *tcp* connection.

In order for these two types of connections to communicate with each other, network bridges with routing functionalities, as described in the next section, were created. Finally the embedded broker is connected with a message broker that runs on the RADIO backend infrastructure, and exposes a set of subscriptions in order to provide an end-to-end connectivity, from the backend until the wireless sensor network. Figure 16 below shows the communication architecture of the gateway.

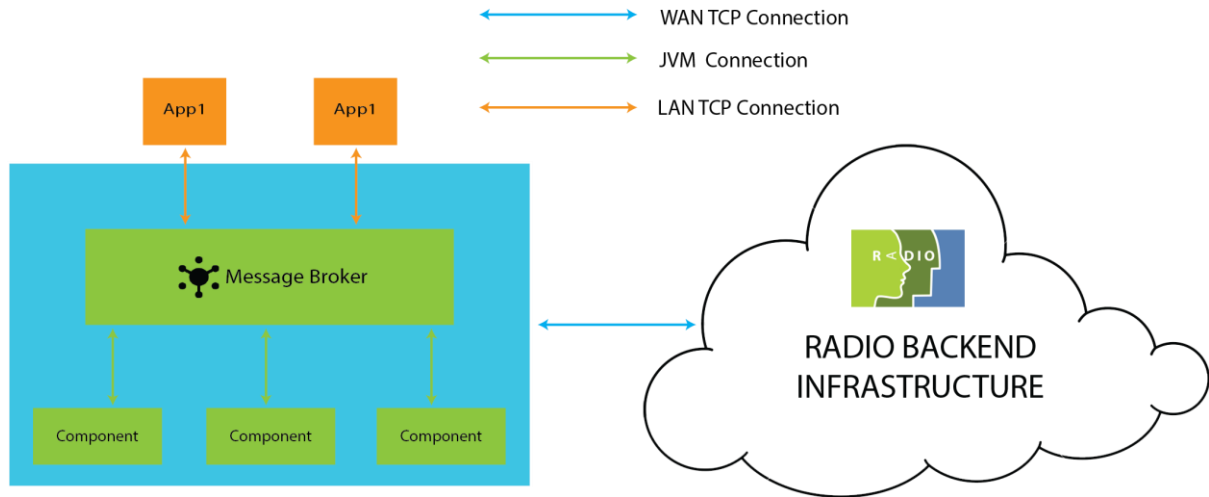


Figure 16 Messaging architecture

This architecture provides massive scalability for a large messaging system, and allows the gateways to be connected together into a network, which offloads the backend infrastructure, from maintaining and handling to many connections. Also allows application-to-application communication, where applications are not running on the same gateway (Operating System). Finally, the communication between the components accomplished, in general, with the MQTT protocol, and the message format used for the messages payload is the Protocol Buffers [ProtoBuf].

5.2.3 Router Component

As mentioned, in the section 5.2.2, due to multiple different connections inside the gateway with the RADIO backend infrastructure a component is needed which is responsible to handle the networks bridges in the gateway internally, in order for the components and applications to communicate with each other. In a typical scenario, on the gateway at least one component exists that connects through the (vm://), and (tcp://) connector to the Message Broker. Also a main connection with RADIO backend infrastructure is available. By adding the Router component, the following features were achieved:

- Communication of components that connected to different connectors.
- Controlling messages traffic, for both inbound and outbound messages.
- Runtime routing capabilities, like destination change.
- Quality of Service (QoS).
- Message transformation.
- Access lists definition.

5.2.4 Scheduler component

As any system, a general component in the architecture is needed that will handle all the repetitive and future tasks. The scheduler component exposes functionalities for other components as well as for the applications, to submit simple, repetitive or future tasks. Each component that wants to run a task, must define the following,

1. The task identifier
2. Scheduling parameters (periodic or not, execution start time, etc).
3. And a callback topic for the task response, if exists.

The scheduler allows executing long running tasks, and monitoring tasks without affecting the main components functionality.

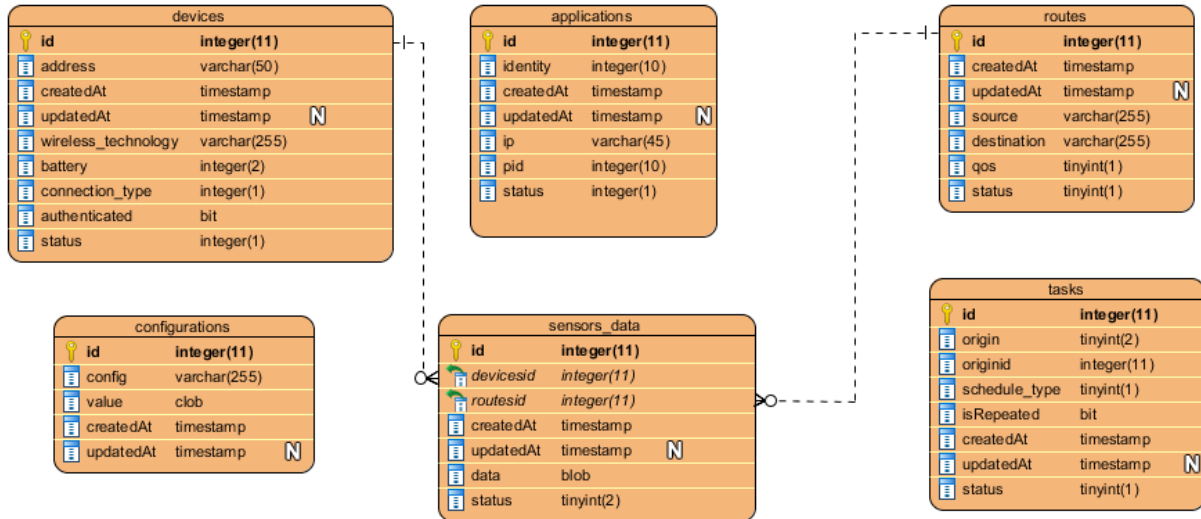


Figure 17 Gateway embedded database scheme

5.2.5 Database component

Our solution provides an embedded database (DB) for a series of actions that will persist in the gateway. We choose SQLite [Bi 2009] as it is a lightweight database and it realizes a complete and embeddable database engine without additional components, which is especially suitable for embedded applications.

The database scheme of our embedded solution shown in the Figure 17 below.

A really small database scheme is implemented, consisting from six tables, which covers all the requirements needed by the gateway in order to operate properly, as well as the requirements for a functional embedded database. More specifically, the database is used to achieve requirements for

- Device registration
- Application monitoring and management
- Configurations retrieval
- Routing
- Task assignment and monitoring
- Sensors data storage

The devices registry represented by the *devices* table which stores all the information about the observed wireless sensor devices, such as the wireless technology of the device (*wireless_technology* column), e.g. Bluetooth Low Energy, as also the connection type of device (*connection_type* column), connection-less or not.

In the *applications* table, as the name implies, all the information about the applications that run on the gateway are stored. The applications, as can be seen in later sections, can be deployed either to the gateway locally or in another devices, which resides inside the network and the communication is through the MQTT protocol. The *ip* column is used in order to identify the location of the application.

The *routes* tables contains routing rules for the data, generated either by sensor devices, applications or the gateway core. The *source* and *destination* columns define the origin and destinations of the generated data, and the *qos* column defines the Quality of Service, for the specific destination.

The *configurations* table contains all type of configurations, such as applications, device and general gateway configurations. The table column, *config*, is the key for the configuration, and the *value* column contains the value of the configuration. The JSON [JSON] format is used for structuring configurations.

The *sensors_data* table contains the data collected from the sensors. Finally, the tasks table records details for tasks running on the gateway

5.2.6 Applications

The *Applications* component of the gateway is responsible to deploy and maintain all user-defined applications of the gateway. The gateway is the data collector and forwarder, where the applications are the consumers and analysers of the forwarded data. Applications reside outside the core of the gateway, and the communication is done using the MQTT protocol. The choice of adding the application outside the core gateway gives significant advantages, which are described below:

1. The applications can be developed in many languages, such as JAVA, C, C++, nodeJS, python and many more.
2. The structure of the application, the tools etc., is at the discretion of each developer.
3. No need to run the applications on the same OS, on which the gateway runs.
4. The deployments of the application is as simple as drag and drop. They just need to be added to the appropriate folder, with some additional metadata for non-executable application, like scripting languages.

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