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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Performance analysis of Bluetooth Low Energy Networks for Wireless Sensors

Laurea Magistrale in Automation and Control Engineering - Ingegneria dell'Automazione

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1. Introduction

With the advent of globalization and the creation of a world market, freight logistic is continuously receiving more and more interest. Specifically, from the point of view of sustainability, pollution reduction and reduced environmental impact, the best available medium appears to be rail transport. In fact it is two to four times more efficient with respect to conventional trucks and its use avoids delays caused by traffic jams and accidents.
Nowadays since it accounts for more than 18% [1] of European freight traffic and foreseeing no signs of regression the main challenge is improving its efficiency to combat one of its main drawback: being not as technologically advanced, monitored and optimized as passenger transport is. This is the reason that lately led the emergence of a new method called **Condition-Based Maintenance (CBM)** in rail transport.
Condition-based maintenance is a strategy that monitors the actual condition of an asset to decide when and which maintenance needs to be done. CBM dictates that maintenance should only be performed when specific indicators show decreasing performance or upcoming failure. It involves monitoring the current condition of equipment or systems using various sensors measurements and data collection techniques, however it is necessary to have real-time control of the entire system and it may require assets modifications to retrofit the system with new sensors.
One of the most recurrent failure with a major impact on traffic safety, reliability and efficiency is related to the breaking system where also a small fault may imply a damaging action on the travelling wagon and the infrastructure itself possibly influencing anomalies of other components meaning greater cost in case of breakdown. That's why we decided to focus on supervising the breaking system.
The bigger problem was that first we wanted to produce a plug-in solution and, since in our application it was not possible to equip each wagon with sensors directly connected to the train power line, we decided to use a completely wireless sensor board. Therefore the major problem we had to dealt with is the control and optimization of the energy consumption.
In this paper we will analyze the state of the art of the already produced sensor board [4], its communication protocol (**Bluetooth Low**

Energy (BLE) [3]) and how we can further upgrade wireless connection efficiency and sensor node placement.

2. State of the Art

Firstly we developed a sensor board equipped with a pressure-meter able to continuously gather measurements through an external connection that must be connected to the main pipe. It must then send them through **BLE** to a central gateway that can transfer and store them in the cloud using a 4G/LTE technology (Fig.1). Regarding the pipe connection part thankfully a train braking system is already equipped with a variety of test-points that we used as a support to mount our smart sensor nodes. As said before

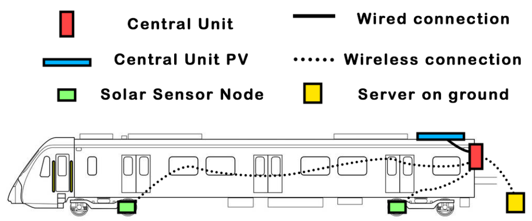

Figure 1: Freight train wireless connection layout.

the main challenge due to the use of wireless sensor boards is energy optimization, leading to the necessity of a power harvesting and consumption reduction method.
First we tested different energy sources and declared the solar one as the most reliable and widely available; that's why every board is equipped with a photovoltaic panel (Fig. 2).
The main components present on board are:

- **Microprocessor**
- Pressure-meter **SSCDANN150**
- **BT840F** (nRF52840 SoC)
- Li-Po **Battery**

For the firmware development part special emphasis was placed on optimizing power consumption by studying it in such a way to balance the minimum time required for operation with the one needed to perform data acquisition and secure real-time analysis.
Moreover to meet energy saving requirements the board firmware was divided in 3 phases:

- **Sleep**

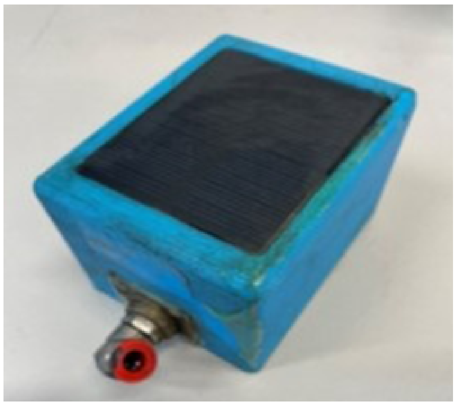

Figure 2: Sensor node

- **Wake**
- **Run**

After start-up the micro is sleeping and waiting for a message to wake-up and begin the Run phase acquiring 20 pressure samples, one every second. When the whole data package is gathered it is sent with battery information, environment temperature and RSSI value through the air to the gateway and the board can now go back to its default Sleep mode.

2.1. Bluetooth Low Energy

To choose the wireless communication protocol a detailed test of the most important ones (ZigBee, BLE, LoRa) led to choosing Bluetooth due to its data encryption feature, low consumption and cost.
Bluetooth is a data transmission standard used in WPAN (wireless personal area network) coming in different versions which most important one is 4.0 that brought us Bluetooth Low Energy (BLE): a completely new technology specifically developed for IoT application and low power consumption systems.
In table.1 below we can appreciate BLE significant features.
BLE devices can act in four different roles:

- Broadcaster
- Observer
- Peripheral
- Central

The first two have the advantage that devices can exchange data without first establishing a connection, the broadcaster sends information while the observer is constantly listening for it. This type of communication is called

Characteristic	Limit
Frequency Band	$2.4GHz$
Channels	40 ($2MHz$ Spacing)
Modulation	GFSK
Data Rate	$2Mbps$
TX Power	$+20dBm$
RX Sensitivity	$-70dBm$
Range	up to $1km$

Table 1: BLE Features

connection-less. While the other ones can exchange data only after a connection has been established between peripheral and central. This type of communication is called uni-cast.
In this application it has been chosen to use every board with a Central configuration and the gateway works as a peripheral establishing a connection to the chosen sensor and gathering the necessary data, once for every available sensor node.

3. Test Kit

In my test case the goal was to exchange information using BLE between two devices and measure protocol's performances: power consumption, error rate and speed.
Since my objective was to only analyze and optimize the communication part I didn't need to use the actual sensor board, but, to make things easier I programmed two Nordic Development Kit (nRF52840-DK) equipped with the nRF52840 SoC and connected both devices to a PC (supervisor) that collects log messages and sends commands through UART interfaces (Fig 3).

On the computer side I used Wireshark Software to sniff BLE over-the-air packets and understand what was happening between the two devices.
Instead, to test power consumption I used the power profile kit provided by Nordic that can measure currents from $500nA$ up to $1A$ with a resolution of $200nA$ and sampling rate of $100kHz$.

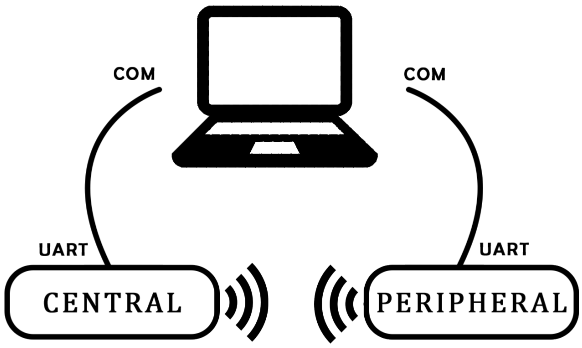

Figure 3: Test Kit Configuration

3.1. Wireless Insite

In pursuit of the best possible energy efficiency sensor transmitter's placement is clearly a crucial choice; in fact if the lowest transmission loss path is found and used the transmitting power can be strongly reduced saving battery drain during connection.
This is where Wireless Insite, a suite that provides 3D Ray-tracing and empirical models for the analysis of radio wave propagation, comes into play. It allows us to built the custom scenario needed with different materials whose characteristic are taken into account for reflection, absorption and diffraction phenomena. It can simulate radio frequencies from $200MHz$ up to $3GHz$ searching for results like received power, propagation path, path loss, reception latency and much more...

4. Firmware

I compiled a firmware built with a pre-compiled stack called SoftDevice [2].
The SoftDevice Application Program Interface (API) is available to applications as a high-level programming language interface implementing a wireless protocol developed by Nordic Semiconductor.
Both Central and Peripheral boards share the same base workflow (Fig. 4) the only difference is that the first one has an advertising state while the other one scans for available peripheral. For the test part I built a $1024KBytes$ memory map to be sent from the peripheral to the central to

average data throughput and energy consumption measurement. I also calculated the theoretically maximum achievable throughput and used it as benchmark to check my results' correctness.

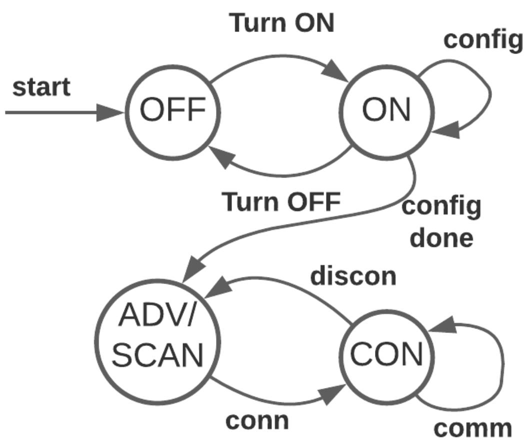

Figure 4: Firmware Workflow

5. Results

During testing I mainly focused on the transmitter (Central) side since it represents the standalone sensor board not connected to a power source which whole implementation gravitates around energy efficiency.
We are now going to discuss obtained results during BLE most important phases:

- **Advertisement**
- **Transmission**

5.1. Advertisement

During the advertisement phase I measured power consumption with various **Transmitting Power** (from $-40dBm$ to $8dBm$) and **Advertising Intervals**. In figure 5 we can appreciate how the instantaneous current consumption grow as the Transmitting power does. Furthermore in figure 6 the current consumption trend is shown with respect to the TX power and it can be easily noticed how there is almost a steady behaviour until $0dBm$ is reached to then face an exponential grow.

Moreover I changed advertising interval with the goal to decrease the average power consumption. It is adjustable from $20ms$ to $10,24s$. Analysing results I noticed that increasing advertising interval will decrease the average current consumption: going from $100ms$ to $1s$ reduce energy drain by 93% (Fig 7).

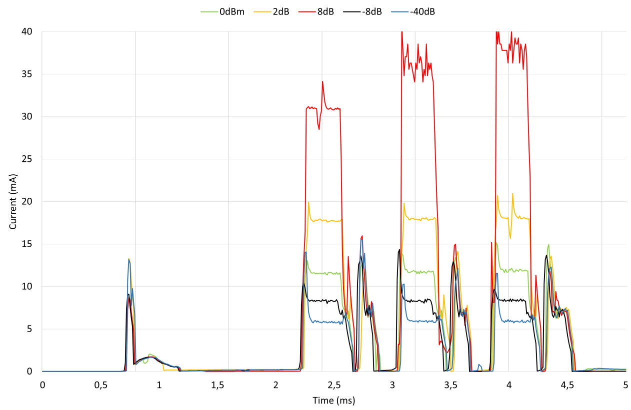

Figure 5: Instantaneous current consumption with different TX power

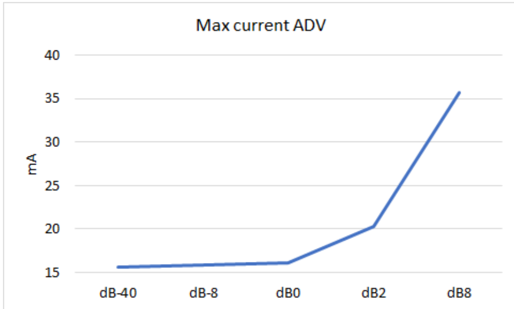

Figure 6: Current consumption vs TX power

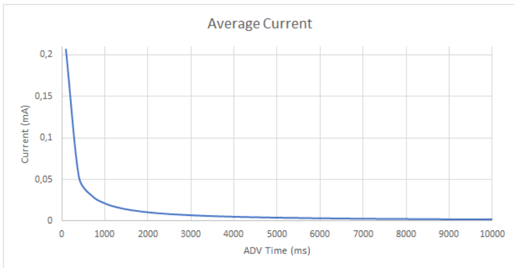

Figure 7: Current consumption vs ADV Interval

5.2. Transmission

During a wireless connection the transmission phase is clearly the most critical one in terms of data throughput and energy consumption. I first theoretically estimated them and later practically measured with respect to different parameters: **Packet Length**, **Connection Interval** and **Physical Rate**.

5.2.1 Packet Length

BLE data packets are equipped with an Header and CRC (14 Bytes) to meet security requirements, this means that the bigger the data length present in every packet the greater efficiency can be reached. In the equation below we can appreciate the estimated throughput with a Packet Length of 251 Bytes and Physical Rate of 2Mbps:

$$T = \frac{(251 + 14) * 8}{2Mbps} = 1060\mu s, \quad (1)$$

$$Duration_{2M} = R + IFS + T + IFS =$$
$$40 + 150 + 1060 + 150 = 1400\mu s,$$
$$Throughput = \frac{Payload}{Duration} =$$
$$\frac{251bytes}{1400\mu s} = 1.434Mbps$$

Where T is transmission duration, R is the reception one and IFS represents the interframe spacing.

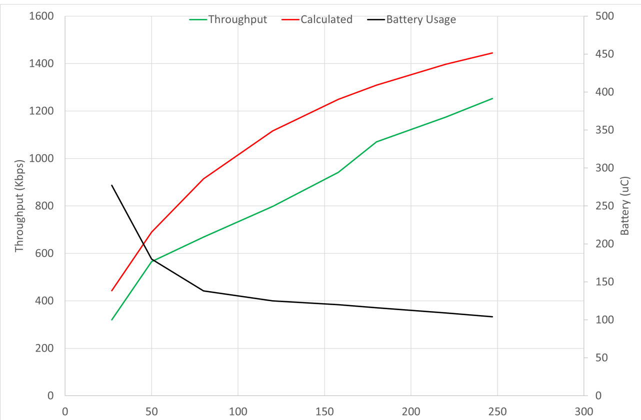

Figure 8: Throughput and Consumption vs Data Length

5.2.2 Physical Rate

Bluetooth Low Energy makes available 3 types of physical layer: $2Mbps$, $1Mbps$, Coded; where the first two are used for short range data transmission while the last one was specifically developed for a long range usage. First I did some calculations again, comparing the $2Mbps$ throughput found above (eq.1) with $1Mbps$ (eq.2) we can see how the data rate almost doubles while doubling physical rate, it doesn't exactly double due to the presence of the inter-frame spacing.

$$D_{1M} = \frac{10 * 8}{1Mbps} + IFS + \frac{(251 + 14) * 8}{1Mbps} + \quad (2)$$
$$IFS = 80 + 150 + 2120 + 150 = 2500\mu s,$$
$$Throughput = \frac{Payload}{Duration} =$$
$$\frac{251bytes}{2500\mu s} = 803Kbps$$

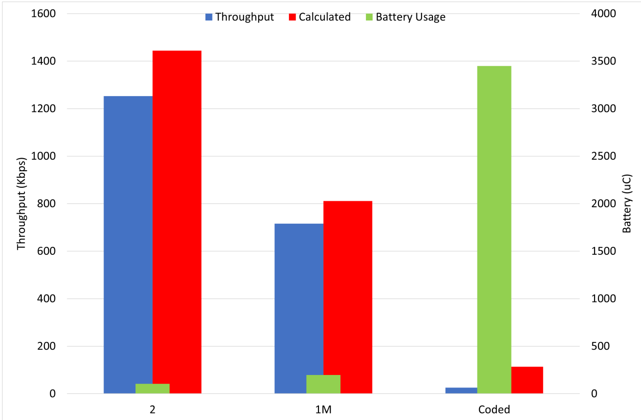

Figure 9: Throughput and Consumption vs Physical rate

5.2.3 Connection Interval

The last parameter tested was connection interval ranging from $7.5ms$ to $400ms$. Looking at the result we see quite a strange behaviour, in fact to obtain the best performance in terms of efficiency data packets must be aligned so that the end of the last packet coincides with the one of the connection interval and it must be avoided to skip packets due to the non synchronization between connection interval and packet's duration.
Here below I calculated the maximum number of packets that can be sent inside a connection event and the relative Time lost.

$$PK_{1M} = \frac{ConnInter}{T_{1M}} = \frac{12000\mu s}{2500\mu s} = \quad (3a)$$
$$\lfloor 4.8 \rfloor = 4packets, \quad (3b)$$
$$T_{lost} = ConnInter - PK * T_{1M} = \quad (3c)$$
$$12000\mu s - 4 * 2500\mu s = 2000\mu s \quad (3d)$$

Results are shown in figure 10. As we can see its tendency is described by a saw-tooth reaching its apex when the packet duration is an exact divider of the interval value: with a $21ms$

connection interval it can send a maximum of 15 packets,84ms 60 packets, 147ms 105 packets and so on…

Since lowering T_{lost} and reducing its ratio with

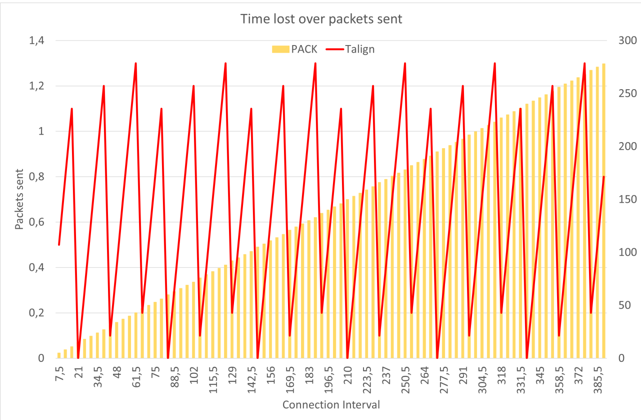

Figure 10: Packet sent and T_{align} with different connection intervals

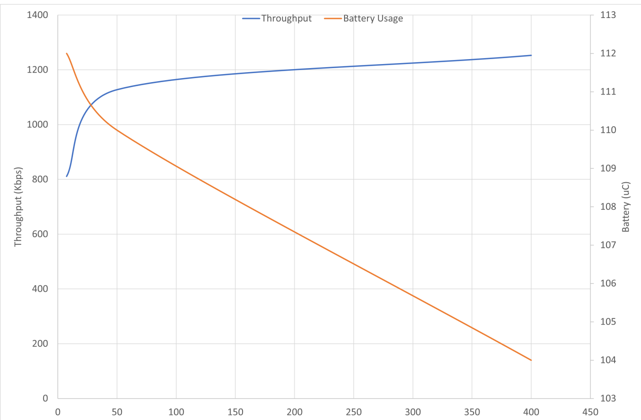

Figure 11: Packet sent and Time lost vs Connection Interval

the packet sent would mean higher throughput it seems obvious to choose a longer connection interval however the following applies:

- Too many packets may be queued while waiting for the next connection interval and you can run out of memory.
- You may have to wait much more to re-synchronize if a connection error occurs. Long connection interval is hence not recommended in noisy environments where CRC errors are expected.

5.3. Propagation Simulation

I also simulated the propagation of BLE waves from the two already placed sensors (MBP and BC) to the gateway in loaded, unloaded train scenario with and without obstacles while gathering transmission loss, propagation paths and total received power.

5.3.1 Loaded and Unloaded Train

Loaded and unloaded scenario can be grouped into the same scenario. In fact we can see how the three best paths in terms of path loss are not influenced by the presence of loading goods due to the fact that no radio waves are propagating above the wagon base (Fig. 12).

Analyzing the results in Table 2, one can see a drastic difference in the power loss of the 3 best paths between the MBP and BC sensor nodes, this is first of all due to the fact that the distance of the BC from the gateway is twice that of the MBP; moreover, the BC is almost completely shielded in its location and its propagation path has to make more reflections before reaching the gateway.

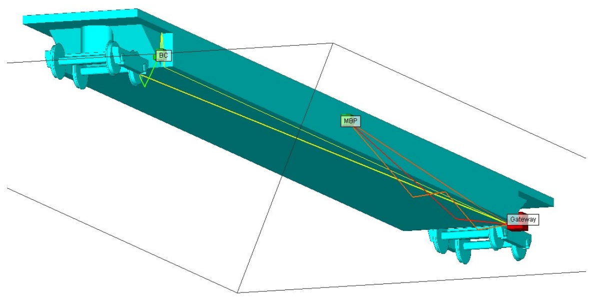

Figure 12: BLE wave propagation in unloaded scenario

	MBP	BC
Path #1	$-71.03dBm$	$-107.7dBm$
Path #2	$-82.37dBm$	$-110.1dBm$
Path #3	$-85.38dBm$	$-121.9dBm$

Table 2: Path Loss in outdoor unloaded scenario

5.3.2 Obstacle presence

For the last simulation phase, I wanted to know whether or not the presence of obstacles in the environment around the train would affect the performances of the transmission and, if so, how.

This is the reason why I studied the system in case the wagon is parked in a warehouse between other trains and when it is passing through a tunnel.
In both these situations I noticed a decrease in path loss, this happens because, instead of obstructing the transmission, the near obstacles work as objects on which BLE waves can reflect improving transmission's efficiency.
We can see all the scenarios expected RSSI in table 3.

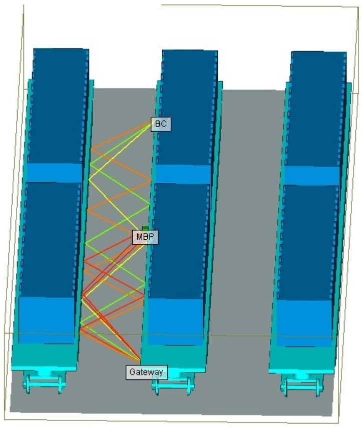

Figure 13: BLE wave propagation in warehouse scenario

	OUTDOOR	WH	TUNNEL
MBP	-68	-55	-54
BC	-104	-68	-100

Table 3: expected RSSI in different scenarios from both nodes

6. Conclusions and future developments

Analysing the results I got it is very simple to understand that the best values in terms of **Data Length** and **Physical Rate** are respectively $251Bytes$ and $2Mbps$. That's why i would suggest to continuously collect measurements and building a memory map long 251 Bytes and send them all together when ready.
While with respect to **Connection Interval** I cannot directly indicate the best value because, as said before, it is related to how noisy the environment is. However I can still tell that the best choice is a multiple of $35ms$ so that T_{align} is perfectly zero.
For the wave propagation simulation Expected RSSI values are shown in table 3 and we understand that the transmission is affected only in a positive way when there are objects around the train. In detail received power tells us that, to establish a secure communication and let our gateway receive the signal, (sensitivity of $-99dBm$) on the MBP side we must us a transmission power of at least $0dBm$, while the BC one must be set to a value higher than $5dBm$. Remember that these are the minimum required value to establish a connection however I recommended to use slightly higher values to not encounter communication errors and having to resend multiple packets with the effect of lowering transmission's efficiency.
Moreover talking about future developments i would suggest to deeply study the waves propagation using Wireless Insite software to find the best possible sensor board's placements and actually test them in real case scenario. In fact from a firmware and protocol optimization point of view I think we already reached the best energy efficiency situation, so only with better positioning we could ensure lower transmission power and receiver sensitivity guaranteeing even lower power consumption.

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