D3.2.1 – Environmental Wireless Sensor Network (WSN) prototypes

Preliminary Version – Results of the first iteration of sensors selection

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Short Abstract

This document describes the outcomes of the first iteration of the sensors selection for developing the environmental monitoring system of NESTORE. The selection followed the recommendations coming from the WP2 activities in terms of needed monitoring variables and tries to address the requirements coming from the WP6 co-design approach. The document also presents an overview of the chosen technologies and their integration in the system using available off-the-shelf devices by means of the Web of Things paradigm.

Key Words

Environmental Sensors, Web of Things, Bluetooth Low Energy, Ballistocardiography, Smart Scale.

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1 Introduction

One of the main goal of NESTORE is to monitor physiological and behavioural data related to the five domains of wellbeing (i.e., physical, mental, cognitive, social, and nutritional). In order to achieve this goal, we develop a multi-domain unobtrusive monitoring system also relevant for assessing the user profile.

In the WP3 activities, NESTORE will optimize and integrate available technical solutions based on advanced non-invasive monitoring systems, such as wearable and environmental sensors (indoor/outdoor).

Focus of this document is the specification of the environmental monitoring system, including sensors for indirect monitoring of behavioural information related to daily living activities patterns and physical activity. This is the outcome of the task "3.2 – Development of environmental sensors".

1.1 Motivation and rationale

The environmental monitoring system is an ensemble of wireless sensors able to sense the variables indicated by the domain experts in the WP2 activities. Furthermore, it has the aim of detecting the interaction of the user with the environment and monitoring the status of the environment itself, in terms of indoor air quality.

For this reasons, we call *environmental* device any sensor deployed in the user's vital space, while *wearable* the device worn by the user during his daily activities. As further source of information about the user's status, we can derive data as result of computation or fusion strategy of data coming from a direct input of the user, as questionnaires, while interacting with the NESTORE coach. We call the latter *soft* data.

Task 3.2 has as main goal to build the integrated environmental monitoring system. To this end, we first performed a technology selection to satisfy not only the requirements coming from the domain experts related to the user profile (to cover as much variables as possible), but also the ones coming from the co-design activities in terms of unobtrusiveness. The integrated system should be unobtrusive under diverse perspectives: user interaction – the user should not wear additional sensors or explicity interact with the environmental device; number of devices – the user's living environment should not be filled with lot of visible devices; installation and maintenance – it should be easy to deploy and maintain the device without additional effort from the user.

Table 1 describes how the device types (*wearable*, *environmental*, and *soft data*) covers the variables indicated as needed by domain experts for each sub-domain and the frequency of transmission. In particular, for some sub-domains, the actual measurements will be sent with a high frequency (e.g. in the case of structured activities suggested by the coach or in the case of detecting social interactions among the user and his caregivers visiting him at home). Other measurement, like a morning weighing, will have a single transmission. As it can be seen in the table, not all the indicated variables are currently covered. This is due to the fact that the outcome of the WP2 activities is the complete modeling of the user status, but some of these variables can be considered stable during the coaching intervention or measured by specialists in ad hoc medical examinations.

In this document, we will focus on the tecnologies used to cover all the variable that are indicated in Table 1 with the column Device Type: *Environmental* (indicated in bold). Regarding the variables covered by wearable device type, we refer to D3.1.1 document for the technocal specifications. For what concerns soft data variables, insights will be available in the D4.1 document.

In the next Section, we will explain how the environmental devices can cover the related sub-domain, in terms of use cases and chosen technologies.

Table 1 Relationships between Device Types and Domains variables. In bold, the sub-domains variables covered by Environmental devices.

Domain	Sub-domains	Device Type	Coverage of Vars	Frequency of Transmission
Physical Activity	Physical Activity Behaviour	Wearable	Medium	High (during structured activities)
	Cardiorespiratory Exercise Capacity			
	Cardiovascular System			
	Respiratory System			
	Strength-Balance-Flexibility Exercise Capacity	**Environmental**	**Low**	**Low**
	Anthropometric Characteristics	**Environmental**	**Medium**	**Low**
	Musculoskeletal System			
	Sleep Quality		**High**	**High** (during sleep)
Nutrition	Energy Expenditure	Soft Data (calculated)	High	Low/Medium
	Nutrition Habits	Soft Data (Questionnaires, Games)	High	Medium
Cognitive, Mental, **Social**	Cognitive Status			
	Mental Status			
	Mental Behaviour and States			
	Social Behaviour	**Environmental**	**High**	**High** (during social interactions)

1.2 Relation with other workpackages

The sensors, whose architecture will be designed on the clinical and utilization requirements provided in WP2 and considered compliant in the co-design phase in WP7, will provide data for the assessment of the user profile and habits, needed for the personalization of the decision support system in WP4 and the coach developed in WP5. The interface technical specifications of the sensors platform will be provided to WP6, for its integration to the NESTORE system.

Figure 1 shows a graphical representation of the relationships between WP3 – T3.2 and the activities of the other NESTORE work packages.

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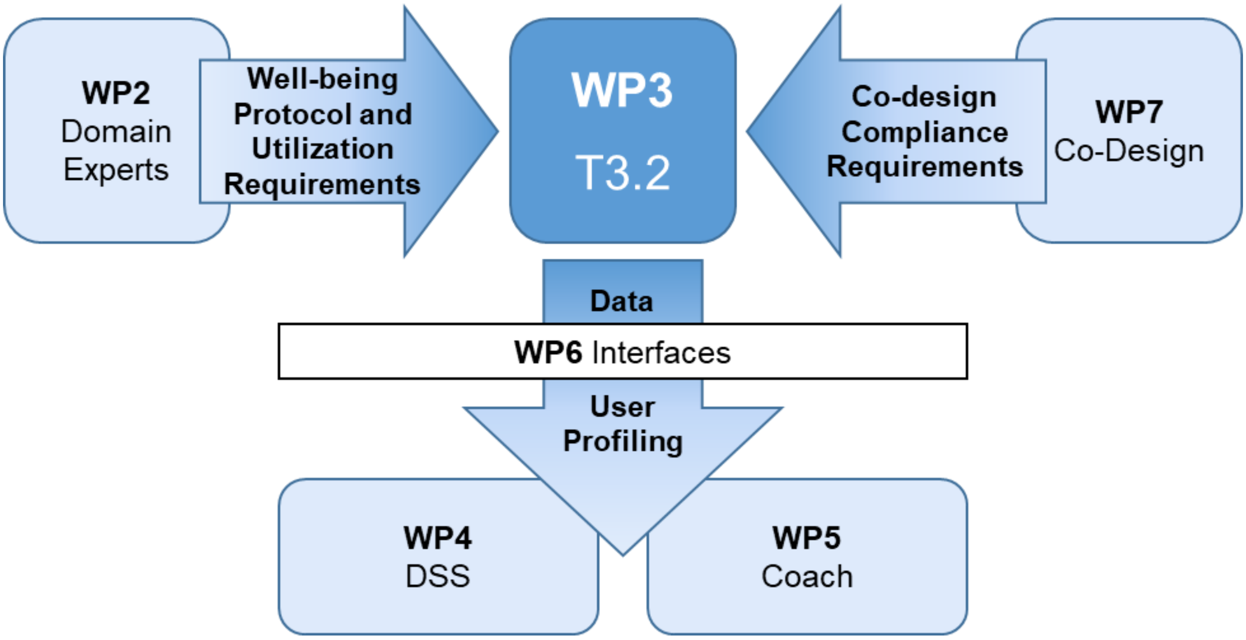

Figure 1 Graphical representation of the relationships between WP3 – T3.2 and the activities of the other NESTORE work packages.

2 Integrated environmental monitoring system

The main goal of task 3.2 is to build an integrated environmental monitoring system able to monitor, mainly using off-the-shelf devices, the environmental data, such as users' house air quality, and the users' behavioural data, such as movements in the house, sleep quality, interactions with point-of-interests in the house and other people.

For each domain, we investigated the possible technologies to be used considering the unobtrusiveness requirements derived from the activities of other work packages. Table 2 shows, for each subdomain, the variables that can be monitored with the chosen technologies.

For anthropometric characteristics and musculoskeletal system, we chose a smart scale able to detect weight and body composition, in terms of percentage of fat mass, muscle mass, water, and bone mass. Regarding the sleep quality, the variables to be monitored (details on the motivations behind these choices can be found in D2.1) are: perceived calm sleep; sleep efficiency; total sleep time; sleep onset and offset; time in bed; sleep onset latency; wake after sleep onset; number of awakenings. We identified in the ballistocardiography (BCG) the best candidate technology for sleep quality assessment, thanks to its easiness of installation, the peculiarity to be contact-less with the user’s body, and good accuracy in detecting physiological raw data during sleep.

For social behaviour, we will use Bluetooth Low Energy (BLE) beacons to detect social interactions among primary users and their relatives (bringing with them keyfobs equipped with mobile BLE tags), monitoring their duration, function, location, and frequency. We will exploit the capability of calculating the proximity between BLE devices from Received Signal Strenght Indicators (RSSIs) also for detecting the interaction of the user with the furnitures in the house on which fixed beacons are deployed, giving us insights on the user’s level of sedentariness.

The possibilities offered by BLE beacons of customizing their hardware and firmware will allow us to advertise, from fixed beacons, additional information like motion (to increase the level of accuracy in detecting interactions with point of interests in the house) and temperature and humidity (to calculate the indoor air quality indicator [1]). Details on each technology are given in the following subsections.

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Table 2 Variables monitored with the identified technologies.

<table>
<tr><th>Domain</th><th>Sub-domains</th><th>WP2 Variables</th><th>Technology</th></tr>
<tr><td rowspan="3">Physical Activity</td><td>Anthropometric Characteristics</td><td rowspan="2">Weight
Fat Mass %
Muscle Mass %
Water %
Bone Mass %</td><td rowspan="2">Smart Scale</td></tr>
<tr><td>Musculoskeletal System</td></tr>
<tr><td>Sleep Quality</td><td>Perceived Calm Sleep
Sleep Efficiency
Total Sleep Time
Sleep Onset
Sleep Offset
Time in Bed
Awakenings
Sleep Onset Latency (SOL)
Wake After Sleep Onset</td><td>Ballistocardiography</td></tr>
<tr><td>Social</td><td>Social Behaviour</td><td>Interaction Duration
Interaction Function
Interaction Locations
Social Interactions Detection
Total Number of Interactions</td><td rowspan="3">BLE Beacons</td></tr>
<tr><td>Air Quality</td><td rowspan="2">T3.2 Activities</td><td>Humidity
Temperature</td></tr>
<tr><td>Sedentariness</td><td>Proximity</td></tr>
</table>

From the architectural and deployment point of view, in order to reduce the effort needed by the end user to install and use the environmental sensors, we chose to adopt a Web of Things (WoT) approach. WoT is a computing concept that describes an environment where everyday objects are fully integrated with the Web. The prerequisite for WoT is for the "things" to have embedded computer systems that enable communication with the Web. Such smart devices would then be able to communicate with each other using existing Web standards.

Considered a subset of the Internet of Things (IoT), WoT focuses on software standards and frameworks such as REST, HTTP and URIs to create applications and services that combine and interact with a variety of network devices. The key point is that this doesn't involve the development of new communication paradigm because existing standards are used [2][3].

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As result of the first iteration of sensor selection, we plan to deploy in a typical NESTORE environment the following devices:

- Fixed BLE beacons installed in meaningful point of interests in the user's home (e.g., fridge, TV, closet, door, table) able to detect the proximity of the user, if the object on which the beacon is installed is moving (useful to detect a opened/closed doors), relative humidity, and temperature.
- Mobile BLE beacons to be provided to secondary users (i.e. caregivers, relatives and friends of the user) in form of keyfobs in order to detect social interactions.
- A smart scale for body composition analysis.
- A ballistocardiograph device for sleep quality analysis.

As depicted in Figure 2, BLE beacons' advertisements will be collected by the smart wristband of the user and then sent to the cloud by means of a WoT agent running on the user's smartphone via WiFI, when indoor, or via mobile connection, when outdoor. The smart scale and the BCG device will send data to the cloud backend via WiFi. Further architectural detail can be found in the D6.3.1 document.

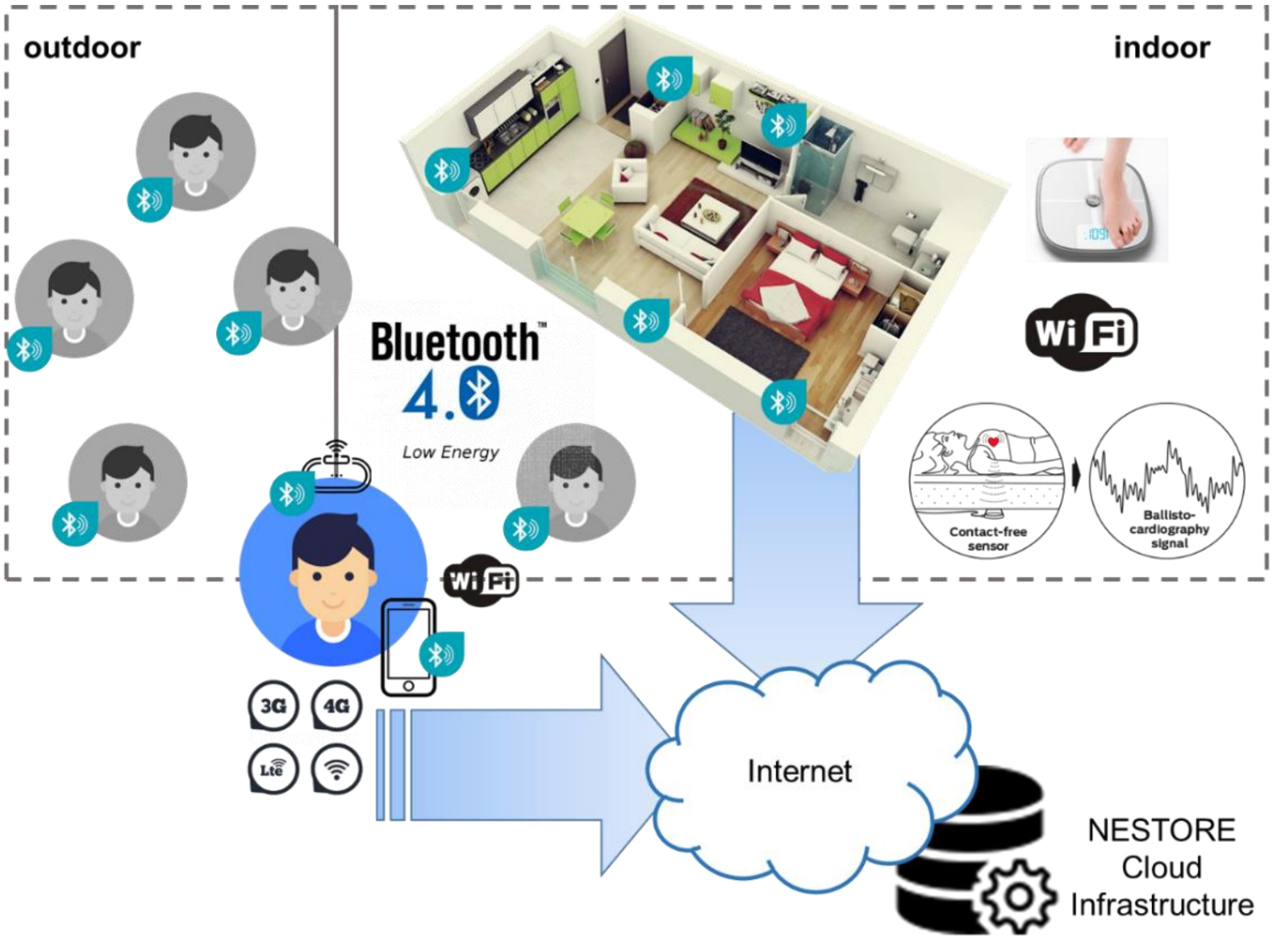

Figure 2 The WoT approach for environmental devices.

2.1 BLE beacons

A beacon, in wireless technology, is the concept of broadcasting small pieces of information. The information may be anything, ranging from ambient data (temperature, air pressure, humidity, and so forth) to micro-location data (asset tracking, retail, and so forth) or orientation data (acceleration, rotation, and so forth).

The transmitted data is typically static but can also be dynamic and change over time. With the use of Bluetooth low energy, beacons can be designed to run for years on a single coin cell battery. This application report introduces the concept of beacons and how to get started with implementing a beacon solution. Naming conventions throughout this document can be summarized as Beacons that broadcast information by using advertisements with Bluetooth low energy technology that could be branded as Bluetooth low energy.

A Bluetooth low energy device can operate in four different device roles. Depending on the role, the devices behave differently. The first two roles are connection-based: *peripheral* - device is an advertiser that is connectable and can operate as a slave in a connection; *central* - device scans for advertisers and can initiate connections. The other two device roles are used for one-directional communication: *broadcaster* - a non-connectable advertiser, for example, a temperature sensor that broadcasts the current temperature; *observer* - scans for advertisements, but cannot initiate connections. This could be a remote display that receives the temperature data and presents it [4].

The two obvious device roles for beacon applications are Peripheral and Broadcaster. Both of them send the same type of advertisements with the exception of one specific flag that indicates if it is *connectable* or *non-connectable*. The low-power consumption of BLE is achieved by keeping the transmission time as short as possible and allowing the device to go into sleep mode between the transmissions.

In the NESTORE ecosystem, we will use non-connectable beacons (BLE devices in broadcasting mode) that simply transmit information that is stored internally. Because the non-connectable broadcasting role does not activate any receiving capabilities, it achieves the lowest possible power consumption by simply waking up, transmit data and going back to sleep. This comes with the drawback of dynamic data being restricted to what is only known to the device. In particular, we will broadcast temperature, humidity, and information regarding the movement of the device in the last time window (using a threshold on embedded accelerometer). The data transmitted by a BLE device is formatted according to the Bluetooth Core Specification [5] and is comprised of the parts shown in Figure 3 and Figure 4.

The first three bytes of the broadcasted data defines the capabilities of the device. When using Manufacturer-Specific Data, the 0xFF flag is used to indicate so. The first two bytes of the data itself are the company identifier code. For non-connectable undirected advertising (ADV_NONCONN_IND), maximum length of the Manufacturer-Specific Data is 28 bytes. The Manufacturer-Specific Data can contain any user-defined information. This will be the case of our solution, being the information that we want to advertise application-specific.

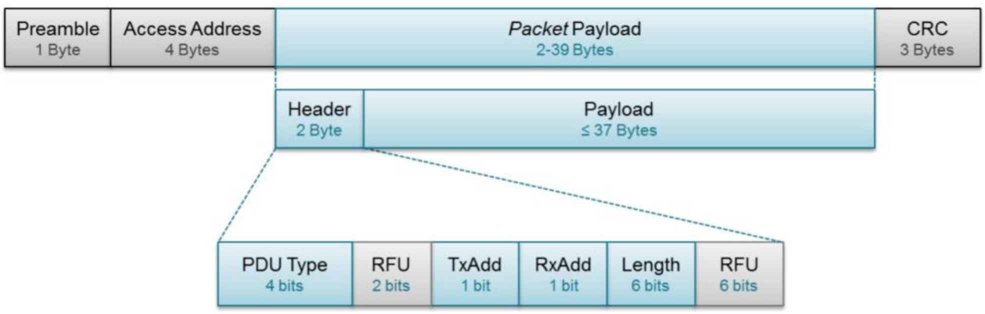

Figure 3 The BLE data packet.

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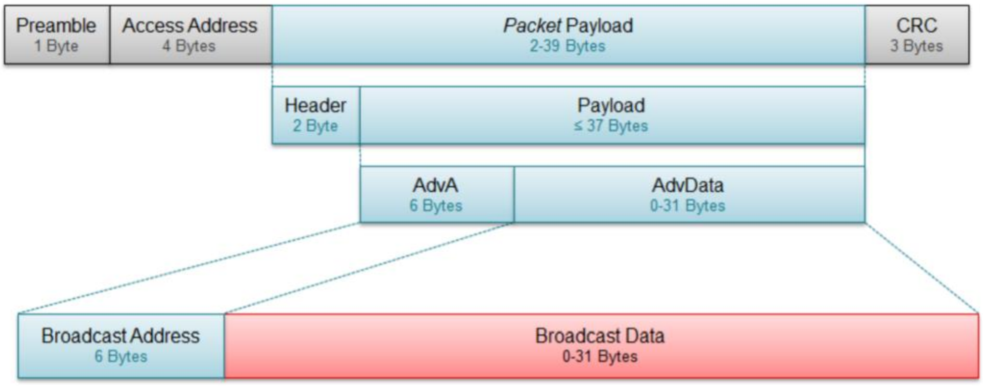

Figure 4 The BLE payload.

The broadcasted data can also be formatted in a standardized way, such as iBeacon from Apple, AltBeacon from Radius Networks, and Eddystone from Google. iBeacon is protected by the MFi license and is interoperable with all iOS devices. AltBeacon and Eddystone are instead open standards and their specification can be downloaded at [6] and [7], respectively.

The sensor selection process considered the capabilities offered by the available BLE beacon manufacturers in order to guarantee the possibility to exploit standard protocols for socialization events interactions (using BLE beacons in form of key fobs) and to modify the AdvData to include air quality information and movements of the beacon itself. Table 3 shows the considered manufacturers in terms of protocol used, possibility to customize the HW and the FW of the beacon, and the price. This analysis lead us to chose the Global Tag manufacturer offering the most customizable BLE solution at a lower price for standard tags, with additional costs for firmware and hardware customization.

Table 3 Manufacturers selection indices

Manufacturer	Protocol	FW/HW Customization	Price
Radbeacon	iBEacon, Eddystone, AltBeacon	No	$
BlueCats, kontakt	iBeacon, Eddystone	No	$$
BlueSense, Estimote, Glimworm, Gimbal	iBeacon	No	$$
Global Tag, BlueUp	iBeacon, Eddystone	Yes	$ ($$ for customization, depending on number of units)

Figure 5 shows the beacons used in our testings for indoor socialization detection, further details about the algorithms used will be available on D4.1 document, while the results from the testing phase in terms of power consumption and data rates will be described in deliverable D3.2.2 (preliminary results can be found in [8]).

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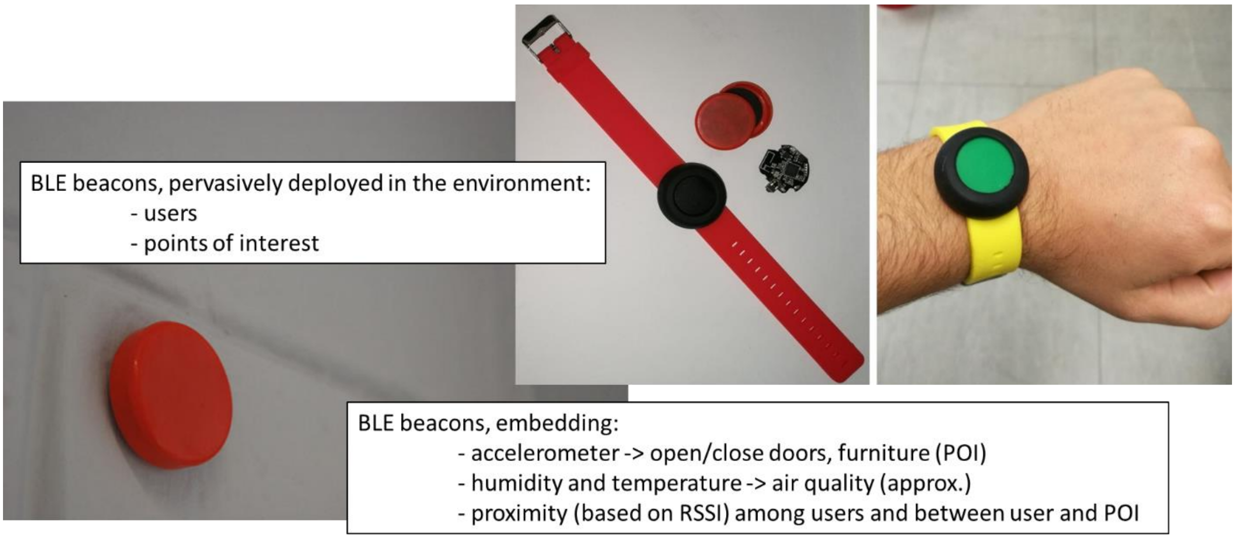

Figure 5 BLE beacons used as environmental sensors and for detecting social interactions.

2.2 Ballistocardiography

Despite being used commonly in sleep medicine, the term "sleep quality" has not been rigorously defined. Usually it refers to well defined questions in dedicated questionnaires. One of the goals of NESTORE is to find a measurable sleep quality index starting from sleep related physiological characteristics. The main variables influencing sleep quality are Heart Rate (HR), Heart Rate Variability (HRV), Resipratory Rate (RR), and Respiratory Rate Variability (RRV). Please see deliverable D2.1 for more insights on the physiological aspects.

From a technological point of view, there are very few ways to monitor sleep quality, among them we find polysomnography (PSG), actigraphy [9], and ballistocardiography (BCG). Being one of the main requirements of the NESTORE system its unobtrusiveness, we easily chose BCG as best candidate.

Ballistocardiography (BCG) is a method for the measurement of the mechanical forces originated from the body [10]. This phenomenon was first studied in 1877 by Gordon and further investigated through the 1900s century. However, BCG was not accurate enough for medical use until recent improvements in the signal processing methods. The new ways to assess BCG signal have produced reliable results when compared with the traditional ECG measurements [11].

In a stationary state, primary mechanical forces acting on the body originate from the heart and circulation of blood, with beating of the heart as a detectable cyclic event. The BCG measurement is physiologically based on the Newton's laws of motion. This force causes a recoil effect on the body that can be visualized in a ballistocardiogram (Figure 6, picture taken from [12]).

The BCG pulse starts when the atria contract, right before the ventricular contraction. The pulse wave maxima and minima are denoted with letters from H to N. The H-K waves form the ventricular systole and L-N waves occur during the diastole which corresponds to the relaxation of the heart. The waves of the BCG pulse are a combination of the forces created by the heart and blood flow. Due to respiratory effect, the I and J waves normally have increased amplitude during inspiration and decreased amplitude during expiration. The sum of all waves roughly represents the relative stroke volume of the heart.

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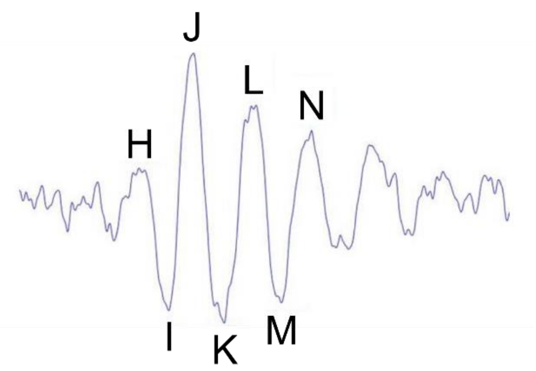

Figure 6 Ballistocardiogram. The BCG pulse is noted with letters from H to N [12].

The magnitude of the forces can be measured as vectors in one direction at a time. Ballistocardiographic forces acting into the longitudinal direction of the body are the strongest and thus easiest to detect. The noise from the environment is small in a stationary state compared to the amplitude of the BCG pulse. BCG devices usually measure only the longitudinal component. Three dimensional BCG is still an evolving research area. Bed or chair systems produce better results compared to ambulatory systems as the subject is generally in still position. In bed, the whole body is longitudinally positioned, further improving the accuracy of single-axis measurements.

In addition to the cardiac events, BCG can be used to detect respiration. Breathing modulates the stroke volume of the heart which is related to the BCG pulse amplitude, as previously explained. The amplitude sum of pulse waves is higher during inspiration and lower during expiration. Respiratory rate can be extracted from the pulse modulation. Respiratory depth is related to the amplitude of the BCG pulse.

BCG enables accurate and non-invasive measurement of the cardiac and respiratory events in a stationary state, i.e. during sleep or rest. Unobtrusive BCG techniques for automatic sleep stage classification have provided good results in continuous home sleep monitoring [13]. The detected cardiac and respiratory events give information about the sleep quality.

A wide variety of different sensors have been recently used in bed-based BCG systems, from static charge sensistive bed and pressure to pneumatic and hysdraulic sensors, but due to its accuracy and low cost, the more commonly used in commercially available products are accelerometers.

For example, resolution of less than 100 µm can be achieved with the Murata SCA11H accelerometer that was utilized in the BCG device for NESTORE studies. High signal resolution and low noise level of the sensor provides advantages in use for sleep analysis. Other commercial BCG based sleep analysis products include Beddit Sleep Tracker [14] and Emfit QS Sleep Monitor [15]. PSG is still used in clinical testing but the BCG products provide an easy way to track sleep over a longer period of time.

As previously said, the rationale behind the performed sensor selection is the possibility to collect data without an explicit interaction of the user with 3rd party applications or the device itself. For this reasons, among the possible BCG solutions available on the market, we have chosen a device able to transmit data over WiFI (in order to not have a dedicate application on the user's smartphone) and that allows us to gather data with available open API. The cost has also been kept in mind. Table 4 shows the considered devices with their characteristics. We also performed a preliminary study about their usability and performance, as shown in Table 5. From the usability point of view we considered how the device is installed, if the user has to manually start and stop the data collection and how he can view his own data. These considerations confirmed our choice of the Murata SCA11H sensor, also because it allows to design our own user interface to be integrated in the NESTORE dashboard. Also the performance analysis confirmed the Murata SCA11H as the best

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candidate, being the sensor that instead of providing an already aggregated and usually unreliable information about user's sleep quality it collect a more rich set of raw data, like HR, HRV, RR, RRV, and Rdepth.

The information shown in Table 5 are the results of a subjective product comparison being performed in home environment by one person, but are a confirmation of the results presented in [12]. Further tests are planned in the next period and they will be shown in deliverable D3.2.2.

Table 4 Manufacturers selection indices

Manufacturer	Connectivity Protocol	API	Price
Emfit QS	WiFi/3G	3rd party cloud with token	$$$
Beddit 3 Sleep Monitor	BT Smart	N/A	$
Murata SCA11H	WiFi	Open both local and remote access	$

Table 5 Preliminary usability and performance analysis of the candidate sensors

	Emfit QS	Beddit 3	Murata SCA11H
Usability			
Installation	Tape	Tape	Attachment plate
Start/close	Automatic	Manual	Automatic
User interface	Complicated	Simple	In development
Performance			
Sleep time	Unreliable	Unreliable	In development
Sleep stages	Yes	No	In development
Cardiac	HR, HRV	-	HR, HRV
Respiratory	RR	Avg RR	RR, RRV, Rdepth

2.3 Smart scale

In order to collect information about the user's body composition, we plan to integrate in the NESTORE system a smart scale able to detect the variables indicated in the D2.1 document (e.g., weight, percentage of fat mass, percentage of muscle mass, percentage of water, percentage of bone mass). All of the considered devices uses Bioelectrical Impedance Analysis (BIA) to calculate the body composition [16]. BIA actually determines the electrical impedance, or opposition to the flow of an electric current through body tissues which can then be used to estimate total body water (TBW), which can be used to estimate fat-free body mass and, by difference with body weight, body fat.

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Also for the selection of the best candidate smart scale solution we considered the easiness of installation and use (no need to manually synchronize a mobile app and the device after a weighing), but also the availablity of APIs to gather the collected data. There is a plethora of smart scale solutions on the market but most of them use dedicated applications on the user's smartphone collecting data via BT and then available on a 3rd party cloud server. An interesting solution for BT smart scales is offered by the openScale project [17]; it is an open source mobile application which supports various Bluetooth scales to keep easy log of the users's body metrics. Also in this case, we need a dedicated mobile application to gather data but this solution can be considered as a valid alternative in case of the integration of a BT scale, thanks to its open source nature. As shown in Table 6, the only available WiFi scales on the market (with a certified level of accuracy) are the NOKIA Body+ and Fitbit Aria 2. These two models are the ones currently being tested In the NESTORE WP3 activities. Further details on power consumptions and reliability tests will be available in document D3.2.2.

Table 6 Manufacturers selection indices

Manufacturer	Connectivity Protocol	API	Price
Generic BT solutions	BT	Ony via mobile app, then cloud with token	$
Open scale solutions	BT	Openscale	$
NOKIA Body+, Fitbit Aria 2	WiFi	Cloud with token	$

3 Conclusions and future plan

This preliminary document (D3.2.2 coming at M24) shows the results of the first iteration in the sensors selection for the environmental devices. As we have seen, with the current set of devices we cover a subset of all the possbile variables in the defined domains. This was expected because the work performed in WP2 activities tried to fully cover the variables affecting the user's life in all of his dimensions. Most of the indicated variables are difficult to be monitored with off-the-shelf devices, but fortunately the frequency of collection is low, therefore it can be done in dedicated shared environment when needed.

Second iteration in sensor selection will aim at enriching the set of sensors and monitored variables, in terms of integrated technologies and devices. The additional devices will be ready to be used in a typical NESTORE environment even if not actually used in the piloting phase of the project. Having an additional set of devices to be used in dedicated shared laboratory will ease the collection of physiological data even if produced outside the NESTORE indoor environment. The availability of additional interated devices will also allow a modular approach in the exploitation strategy: if a NETORE user needs a particular device for a specific aspect of one of his domains, the device will be ready to be added to the NESTORE ecosystem at a later time.

Also for the already integrated devices we plan to extend their use in collaboration with WP4 and WP5 work group. In particular, the presence of BLE beacons in the house can be exploited for monitoring sedentariness of the user, fusing the information coming from the smart wristband, and to augment the user interaction experience with the tangible interface developed in the WP5 activities. Furthermore, recent developments in the WP3 activities also opened the possibility of designing, developing and integrating the BLE technology by the NESTORE consortium, using the expertise offered by FLEX. Some preliminary insights can be found in deliverable D3.1.1, while the complete integration process with testing will be available in document D3.2.2.

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