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Agent-oriented Integration of Body Sensor Networks and Building Sensor Networks

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Abstract*—In this paper we propose an agent-based approach for the integration of building networks (BNs) and body sensor networks (BSNs). Such an integration has the potential to enable a novel set of smart environments for ambient assisted livings further enhancing the concept of smart buildings. Specifically, inhabitants of buildings who are equipped with a BSN can expose their real and virtual sensed data to the BN that can use them to effectively support differentiated services: people identification and localization, information exchange, safety, security, and context-aware personal support. The proposed approach currently uses a gateway developed in JADE interfacing BNs based on the BMF framework with BSNs based on the SPINE framework. A system use case is shown that elucidates the BN/BSN integration based on the agent gateway. Finally, an evaluation of the overhead introduced by the defined application-level solution is also provided.

I. Introduction

A WIRELESS Sensor Network (WSN) [1] is a collection of tiny devices capable of sensing, computation and wireless communication operating in a certain environment to monitor and control events of interest in a distributed manner and collectively react to critical situations. WSN applications span various domains such as environmental and building monitoring and surveillance, pollution monitoring, agriculture, health care, home-automation, energy management, earthquake and eruption monitoring.

When applied to the monitoring of human body parameters, WSNs are usually called Wireless Body Sensor Networks (WBSNs) [2], or simply BSNs. They can significantly improve the quality of human life by enabling continuous and real-time medical assistance, e-fitness/e-wellness, and daily life activities support at low cost [3].

WSNs applied in the context of buildings are typically referred as Building Wireless Sensor and Actuators Networks (WSANs) [4], or simply Building Networks (BNs). BNs aim at satisfying different needs of inhabitants of buildings such as awareness regarding their structural health, control over the building environment, actuation of specific policies in the energy management of buildings, trade-off with respect to energy consumption and people comfort, support for context-aware social and commercial activities, safety and security.

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In order to effectively provide such services, buildings are required to become "smart" [5] [6] [7] [8] and "human-aware" so being able to implicitly and explicitly interact with their inhabitants. To realize this vision, BNs and BSNs worn by buildings' inhabitants could be seamlessly integrated so that real and virtual data sensed from people can be exposed and collected by the BN. Such an integration poses interesting technical challenges at different layers: protocols, devices, and software.

In this paper, we propose an effective solution based on the concept of *gateway*, a software component interfacing BSNs with BNs at application-level. In particular, the role of the gateway is to interpret requests coming from the BN about sensing people's vital parameters (e.g. body temperature, heart rate, human activity, emotions) and send the sensed data to the BN according to the specific requests. The gateway is currently implemented on JADE [9] and, specifically, integrates BNs based on the Building Management Framework (BMF) [4] with BSNs based on the SPINE framework [10].

The rest of the paper is structured as follows. Section II introduces some related work on heterogeneous networked system integration. Section III discusses benefits and technical issues of BN/BSN integration and provides an application-level solution based on gateway. In Section IV, we first briefly introduce the BMF and SPINE frameworks and then present the design of the gateway based on JADE. Section V presents a system use case along with some technical details about the implemented solution and an evaluation of the overhead introduced by the JADE gateway. Finally, conclusions are drawn and direction of future work delineated.

II. Related Work

The integration of heterogeneous networked systems is an important problem which has been addressed in different research and industrial contexts.

In [11] authors addressed the problem of integrating autonomous and heterogeneous IT systems that are not correlated so allowing for automatic monitoring across systems that would otherwise require manual intervention. They designed and implemented the NETA Monitoring System which is based on standard agents standing on different platforms. These agents report, in an asynchronous fashion, events to a System Engine, which is the core of the NETA Monitoring System. It is in charge of correlating events and managing any trouble for each platform.

Integration of different classes of networks is instead the aim of [12] where authors describe two possible integration approaches (tight and loose integration) and implement the latter. The development of the loose integration approach is based on the introduction of two components in the system: a new network element called IOTA (Integration Of Two Access technologies) gateway deployed in the network and a new client software. In particular, the IOTA gateway cooperating with the client software offers integrated 802.11/3G wireless data services that support seamless inter-technology mobility, Quality of Service (QoS) guarantees and multi-provider roaming agreements.

Integration has been also notably carried out based on agent technology. In [13] authors design and implement a framework which uses mobile agents to ensure information exchange between legacy network management systems and a top management layer. Their aim is the realization of an evolutionary network redesign which preserves the existing infrastructure and saves the operator's existing investments. The framework is based on layered decentralized management architecture, and implemented using agents on the net and subnet layers. The application of the solution is demonstrated in the framework implementation with the Aglets mobile platform [14] used as the toolkit for the mobile agents implementation.

In [15] authors present a novel agent-based approach to data translation between WSN and an existing agent-based air condition monitoring system. Their aim is demonstrating that a multi-agent approach combined with wireless sensor networking can be used for a number of air condition monitoring applications. They designed and implemented a sensor network gateway which provides an interface between the JADE FIPA-based multi-agent system and the wireless sensor network. It consists of a FIPA-compliant gateway agent and a physical sensor node configured to act as a basestation at the edge of the sensor network.

In [16] authors present the design and implementation of the JADE/MAPS gateway. It allows integration between two agent platforms, namely JADE [9] (Java Agent DEvelopment Framework), which is used for conventional distributed environments, and MAPS [17] (Mobile Agent Platform for Sun SPOTs), which is exploited in WSNs. Thus the gateway enable also the integration of distributed platforms and WSNs. The gateway has been implemented as a JADE agent to provide a communication mechanism between JADE and MAPS agents so facilitating bi-directional translation between JADE ACL messages and MAPS events and supporting routing of communication between the two agent platforms.

III. Integrating Building Networks and Body Sensor Networks

The integration of BNs and BSNs aims at facilitating the development of novel smart environments, namely human-aware smart buildings, effectively supporting people while they enter and move inside (residential, commercial, public) buildings. The main supporting services are:

- *People identification*, which is fundamental to identify people inside the building. This service is the basis for more advanced services related to security and personalized people support.
- *People localization*, which allows to trace the location of people inside the building.
- *Information Exchange*, which enables the transfer of different kind of information between people and the smart building. For instance, the smart building could monitor the vital parameters of people for health-care assistance.
- *Safety*, which supports people in case of emergency. For example, this service could suggest the safest pathway/s to exit the building in case of a fire alarm.
- *Security*, which supports security of building by monitoring authorized/unauthorized people and enforcing space access.
- *Context-aware personal support*, which is based on the first three basic services and provides specific services depending on the type of buildings and context in which people are located. For instance, in a commercial building such as a mall, the smart building could send advertisements to people depending on their captured emotions while approaching and visiting shops.

Different types of BN/BSN integration can be envisaged at different layers (see Fig. 1):

- *BN and BSN use the same protocols*. In this case, BN and BSN have to be homogeneous (same physical, MAC, network and application layers) so that BSN nodes seamlessly become members of the BN.
- *BN and BSN only have different physical layers*. In this case, BN and BSN have to be homogeneous at the MAC, network and application layers and have to interact through hubs in the network that translate the data between different physical media.
- *BN and BSN have different physical and MAC layers*. In this case, BN and BSN have to be homogeneous at the network and application layers and have to interact through bridges in the network that translate the data between different MAC layers. Moreover, bridges can apply filtering on the MAC addresses of the packets that are not addressed to the subnet they manage.
- *BN and BSN have different physical, MAC and network layers*. In this case, BN and BSN have to be homogeneous only at the application layer and have

to interact through routers that merge networks running different network protocols (usually BNs use multi-hop network protocols while BSNs use star-topology single-hop protocols). Routers can filter data based on destination addresses.

- *BN and BSN implement different physical, MAC, network and application layers*. In this case, BSN and BN need to interact through an application gateway. So, BSN and BN are independent and share a node that acts as a gateway between the two different networks. This node knows both the BSN and the BN communication protocols at all layers and will translate data between the networks at application layer.

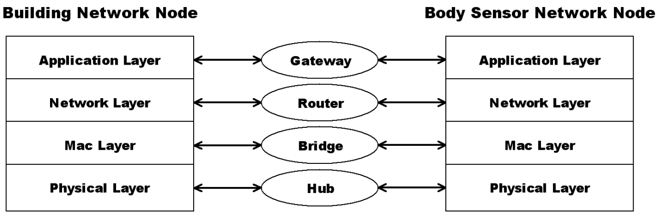

Fig 1. BN/BSN integration at different layers.

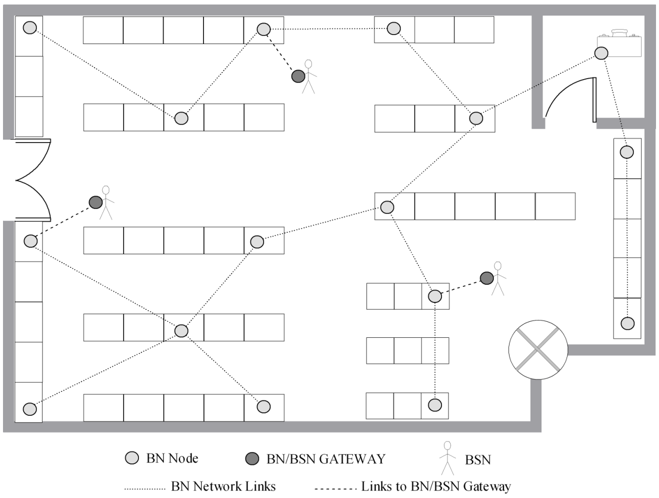

Fig 2. BN/BSN gateway-based interaction.

Among the aforementioned integration approaches, we believe that the application gateway is the most suitable and viable one because it allows to use different protocol stacks for BNs and BSNs and also different transmission media. This also allows for a high degree of heterogeneity of the involved devices (coordinators, sensors and actuators) and avoids interoperability issues at different layers. The most suitable node on which to install the gateway is represented by the BSN coordinator (see Fig. 2) as we can assume that each BSN has a powerful coordinator (smart-phone, tablet, PDA) with (i) a specific node interfacing the BN and actually being a (mobile) node of the BN, and (ii) a specific node interfacing with the BSN nodes. To the best of our knowledge, the solution we present in this paper is the first one that addresses the integration between different kinds of WSNs, namely BN and BSN.

IV. The Agent-based Gateway

The reference architecture of the proposed solution is shown in Fig. 3. The defined application-level gateway interfaces BMF-managed BNs, which are formed by a multi-hop network of wireless sensors and actuators, with SPINE-based BSNs, which are composed of a single-hop network. In the following subsections we first provide some basics about the BMF [4] and SPINE [10] frameworks and then present the JADE-based design of the gateway.

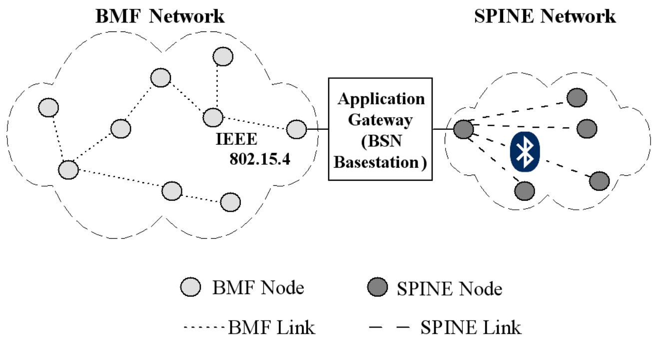

Fig 3. BN/BSN gateway network architecture.

A. The Building Management Framework

The BMF [4] [18] is a domain-specific framework available both for WSAN nodes and for WSAN coordinators (BS-side) such as PCs or smart-phones. The BMF provides flexible and efficient distributed sensing and actuation in buildings and in all other contexts in which sensors/actuators can be deployed in environments and on physical objects. The main features of the BMF are: quick node reconfiguration, processing algorithms implemented on the nodes, multi-hop networks support, hardware and software cross-platform support, provision of a building programming abstraction (namely dynamic groups) to model from a high level point of view the morphology of buildings/physical spaces, actuators support, and flexible and extensible library to program application on top of the BMF.

The BMF architecture (both BS-side and sensor node-side) is shown in Fig.4 in a layered fashion. Moreover, Fig. 4 shows how coordinator and sensor nodes interact through an application-level BMF communication protocol that is based on a multi-hop network protocol. The BMF permits to build applications on top of it providing an API that allows the communication between the application and the WSAN coordinator. In particular, an application can interact with the *Request Scheduling* layer to schedule sensing and actuating operations. This request scheduling can be sent to single nodes or dynamically created groups of nodes. At the node-

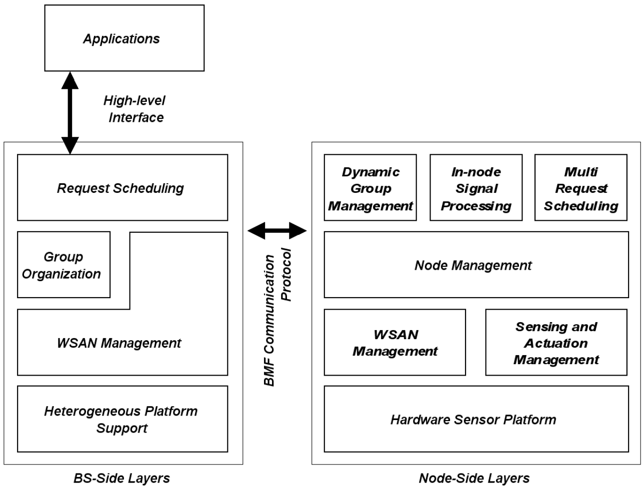

Fig 4. The BMF architecture.

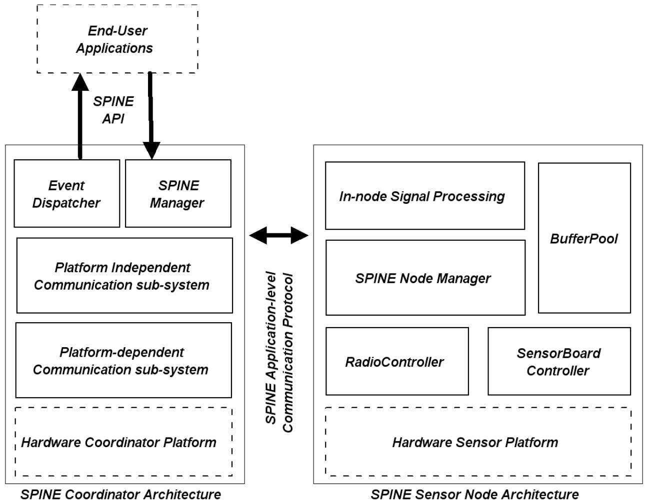

Fig 5. The SPINE architecture.

side, the *Multi Request Scheduling* layer is able to execute multiple requests sent from the coordinator.

B. The SPINE Framework

The Signal Processing In-Node Environment (SPINE) Framework [10] [19] is a domain-specific framework for programming BSN applications.

SPINE supports networks organized with star topology, with one coordinator node as center of the star and one or multiple sensor nodes as edges. This design choice fits the BSN domain requirement for which the wearable sensor nodes stay within radio range and communicate only with their own coordinator device.

The wearable devices can be equipped with several type of physiological sensors and are able to wirelessly transmit raw sensor signal as well as locally processed sensor data to their corresponding coordinator. The coordinator device (which can be a PC, smart-phone or a tablet) is, instead, in charge of managing sensor nodes setup, signal acquisition, processing, and storage and if necessary may forward the physiological signals or higher-level patient status information to Internet servers or Cloud services to enable remote monitoring.

The software architecture of SPINE consists of two macro entities (see Fig. 5), implemented, respectively, on the coordinator (in Java for PCs and Android for smart-phones and tablet) and on the wearable nodes (in TinyOS for Shimmer, TelosB, and MicaZ platforms, and Z-Stack for Zigbee-compliant sensor platforms).

End-user applications run on the coordinator and BSN control (i.e. sensor setup, signal processing configuration, and data transmission) as well as BSN events and data notification are simplified by the lightweight and intuitive SPINE API. On the node side, SPINE supports developers with abstractions of hardware resources (e.g. sensors and radio), a default set of ready-to-use and general purpose signal processing functionalities and, most important, with a flexible and modular architecture to customize and extend the framework itself if application-specific modifications (in terms of new physical sensors to support or particular on-node signal processing functions to implement) become necessary.

Moreover, the SPINE framework includes an application-level (meaning independent from the underlying network and data-link layers) communication protocol to manage the bidirectional communication between nodes and the coordinator.

C. The JADE-based Gateway

The JADE-based gateway is a multi-agent system composed of two interacting JADE [9] agents: the BMFAgent and the SPINEAgent.

Multi-agent system technology was chosen due to its capability of flexibility and extensibility, as demonstrated in [15] and in [16], where it is shown that a multi-agent approach is able to effectively support wireless sensor networking for integrating different kind of networks. Moreover, both in [15] and in [16] JADE is used as agent-based platform for the system implementation.

The BMFAgent interfaces the BMF network by encapsulating and enhancing the behavior of a BMF node (see Sect. III.A). From the BMF network perspective, the BMFAgent is just a BMF node interacting with the BMF coordinator by using the BMF protocols.

The SPINEAgent interfaces the SPINE network by encapsulating the SPINE coordinator (see Sect. III.B). From the SPINE network perspective, the SPINEAgent is just a SPINE coordinator interacting with the SPINE nodes through the SPINE protocols.

The ACL-based interaction between the two gateway agents and the BMF Coordinator is reported in the interaction diagram of Fig. 6. In particular, as soon as the gateway is activated, the BMFAgent requests the list of available sensing services to the SPINEAgent. A sensing service is based on either real or virtual sensors. When the BMFAgent receives the reply from the SPINEAgent, it sends the advertisement message (AD-PKT) to the BMF Coordinator, advertising the available data services. Such message is indeed sent periodically. As soon as the BMF Coordinator receives the advertisement message, it includes the BMFAgent in the BMF network as a BMF node. From now on, the BMF Coordinator can issue request messages (REQ-PKT) targeting the BMFAgent which, in turn, replies with an acknowledgment message (A-PKT). Currently the BMFAgent is able to interpret two types of sensing requests:

- *One-shot*, which allows to request a single reading of raw or aggregated sensed data from selected sensors;
- *Periodic*, which allows to set up periodic readings of raw or aggregated sensed data from selected sensors.

A request can also be *Threshold-based*, which allows to perform a single reading (or periodic readings) of raw or aggregated sensed data from selected sensors when such data are compliant with defined threshold-based operations: >t(hreshold), <t, >=t, <=t, =t, $[t_1,t_2]$.

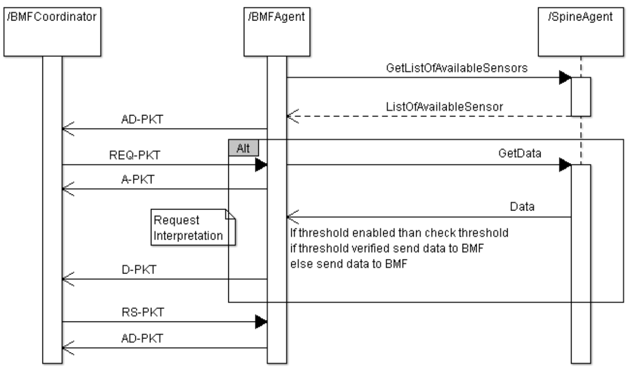

Fig 6. Interaction among BMF Agent and SPINE Agent.

After request interpretation, the BMFAgent creates and add a JADE OneShotBehavior executing the simple or threshold-based one-shot request or a JADE CyclicBehavior executing the simple or threshold-based periodic request. Such behaviors are able to request data to the SPINEAgent and according to the request logics, they process received data and send data messages (D-PKT) to the BMF Coordinator.

If the BMF Coordinator wants to stop any data message from the BMFAgent, a reset message (RS-PKT) can be sent to the BMFAgent that will layer start sending AD-PKT to the BMF Coordinator.

Specifically, the structure of the BMFAgent and the SPINEAgent are respectively reported in Fig. 7 and Fig. 8.

In particular, the BMFAgent is composed of the following classes:

- *BMFAgent*, which is the main BMFAgent class. It extends the JADE Agent Class and keeps track of all the instantiated behaviours. Moreover, BMFAgent Class has a composition relationship with the BMFInteraction class;
- *BMFInteraction*, which is the component allowing the interaction with the BN. It implements the BMF communication protocol [4];
- *BMFBehaviour*, which interprets the requests sent from the BN and instantiates new one shot or periodic behaviours. It communicates with the SPINEAgent through ACL-based messages to get the list of the available sensors in the SPINE-based system;
- *OneShotBehaviour*, which is the Behaviour which allows managing one-shot requests, either threshold-based or not. It communicates with the SPINEAgent through ACL-based messages to receive data from sensors;
- *PeriodicBehaviour*, which is the Behaviour managing Periodic requests, either threshold-based or not. It communicates through ACL-based messages with the SPINEAgent to retrieve data from sensors.

It is worth noting that BMFBehaviour, OneShotBehaviour and PeriodicBehaviour extend the JADE Behaviour class.

The SPINEAgent is composed of the following classes:

- *SPINEAgent*, which is the main SPINEAgent class. It extends the JADE Agent class. SpineAgent has a composition relationship with the SPINEInteraction class;
- *SPINEInteraction*, which is the component allowing the interaction with the BSN system. It implements the SPINE communication protocol;
- *SPINEBehaviour*, which is the component allowing the interaction with the BMFAgent through ACL-based messages. In particular, it provides the list of available sensors, senses data from sensors and sends sampled data to the BMFAgent. It extends the JADE Behaviour class.

Finally, the gateway has a mechanism dealing with mobility: a problem which can arise in this kind of scenarios is that a gateway can be temporarily offline because it is far from any BN node or because the handoff procedure is not instantaneous. In this case, some data packet from the gateway to the BMFCoordinator can be lost. To overcome this problem, at the low level of the gateway an intelligent buffer has been implemented; it stores the data to be sent to the BMFCoordinator and, once online, sends all the buffered data to the coordinator.

V. A System Use Case: Physical Activity Monitoring in Buildings

Physical activity recognition is one the fundamental building blocks of many BSN applications [20]. It is necessary to monitor daily activity levels for wellness applications; it may help identifying abnormal heart rate variations, e.g. by correlating the rate variations with the current activity being performed, and it can be applied in highly-interactive computer games, to cite a few scenarios.

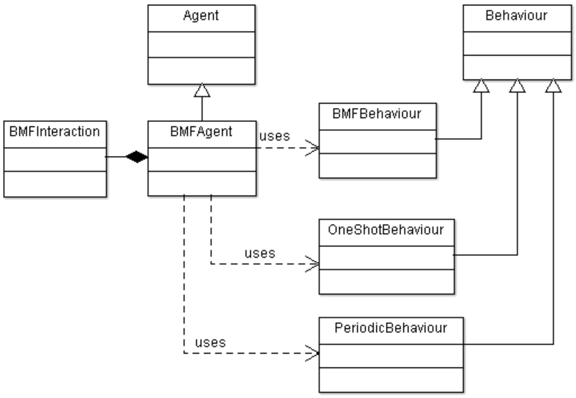

Fig 7. BMFAgent architecture.

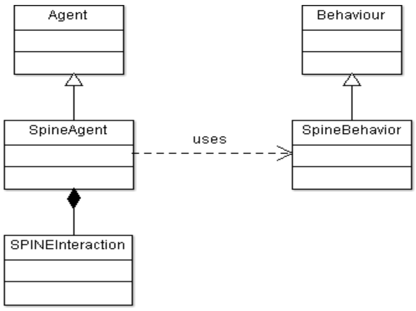

Fig 8. SPINEAgent architecture.

Smart buildings can monitor activities of their inhabitants to better support them for basic and customized services (see Sect. II).

The proposed in-building human activity monitoring system architecture is shown in Fig. 9. It is an instantiation of the architecture of Fig.2 consisting of the BMF Coordinator, the BMF network, and pairs of a JADE Gateways with a SPINE-based BSN system. In particular, our SPINE-based BSN system [19] [21] uses only two wireless motion sensor nodes placed on the waist and on the thigh of the assisted living, and a personal smart-phone (or a PC) running the end-user application which is able to detect four basic activities (lying down, sitting, standing, and walking). This is achieved with or without an individual training phase, and with an overall average accuracy of about 98%. Furthermore, the system may also report the number of steps during walking, and detect the event of accidental falls that may potentially lead to dangerous situations (e.g. if, after a detected fall, the system recognizes the subject is lying down for several minutes). Finally, it also provides an incremental learning system that users may use to increase the set of activities that can be recognized (e.g. to add a “kicking” or “jumping” activity).

The system allows for different monitoring modes that can be easily and dynamically programmed by the BMF Coordinator: *continuous*, *on-demand* and *alert-based* activity monitoring. Continuous monitoring mode supports continuous acquisition of the human activity status according to a programmable sampling rate. The on-demand monitoring mode allows to query the current status of the human activity. The alert-based monitoring mode can detect specific transitions (e.g. sit to stand) or events (e.g. falling) of the human activity and, on their detection, can send out alerts. This system feature is essential to configure personalized monitoring on the basis of people identity and fulfill specific collective objectives.

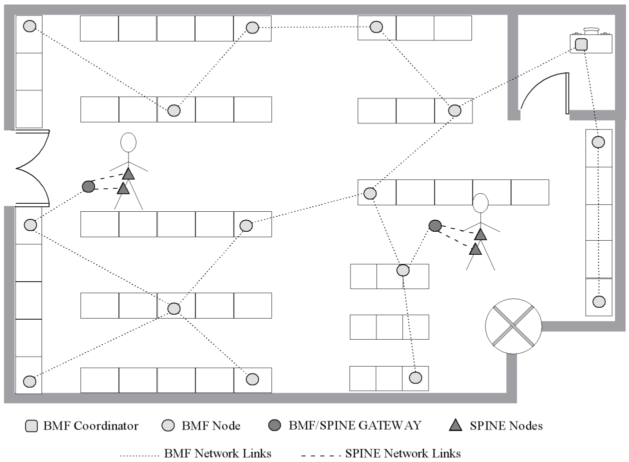

Fig 9. Architecture of the in-building physical activity recognition system.

VI. Performance Evaluation of the JADE-based Gateway

The developed JADE-based gateway was evaluated in the system use case presented in the following. In particular, the evaluation was aimed at computing the forwarding time of the gateway which can be defined as the sending time of the data sensor request issued by the BMFAgent plus the sending time of the data sensor response sent by the SPINEAgent. A careful evaluation of the forwarding time is important as it could affect the remote sensing driven by the BMF Coordinator by introducing jitter and drift.

The evaluation consists of seven test of periodic requests for raw data from the 3-axes accelerometer of a wearable sensor node worn by a person. The considered sampling times are ST = *20ms, 25ms, 50ms, 100ms, 250ms, 500ms, and 1000ms* while the duration of each run is *D = ST * 1000* to have a significant sample of data for each experiment.

The average forwarding time with its standard deviation per sampling time is shown in Fig. 10, whereas Fig. 11 shows the average jitter with its standard deviation per sampling time.

A conclusion that can be drawn from these experiments is that the proposed gateway can support very high data rates since the forwarding time is very low at every considered sampling time even though, since the average jitter is positive, drift could be introduced on acquisition times.

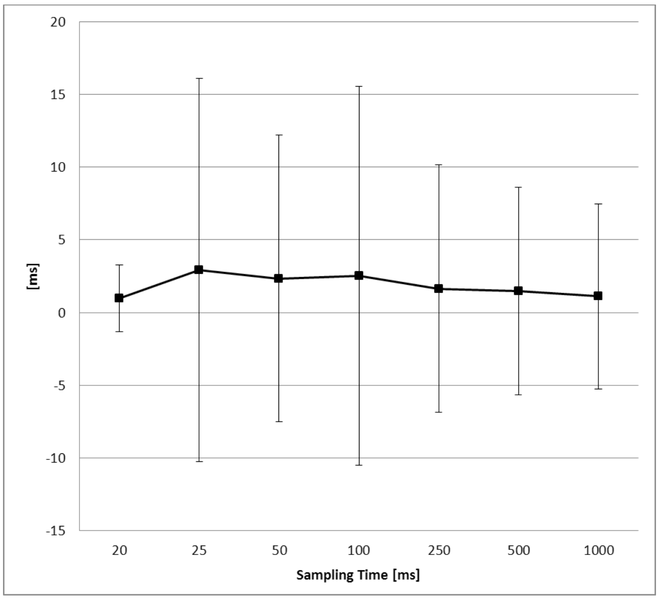

Fig 10. Average forwarding time and its standard deviation.

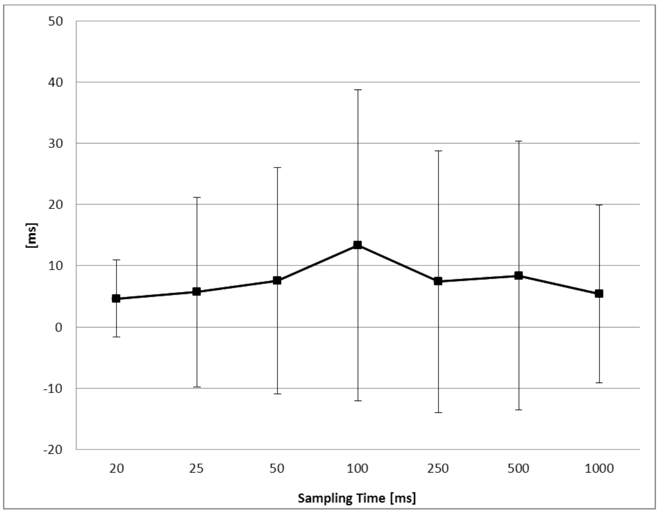

Fig 11. Average jitter and its standard deviation.

VII. Conclusions

This paper has presented an agent-based approach for the integration of BSNs and BNs for the purpose of enabling new smart personal services in the context of next generation smart buildings. The approach centers on an application-level gateway that is able to make seamlessly interoperate a BMF-managed network with a SPINE-based system. Specifically, JADE has been employed as agent-based framework for developing the gateway solution. A system use case concerning real-time monitoring of the activities of people in a building has been discussed. Finally, the performance evaluation of the gateway has shown the suitability of the JADE-based gateway to support high sampling sensor rates. On-going work is geared at evaluating the entire developed in-building human activity monitoring system within our department. Specifically, the testbed is set up to account for an area of the department managed by a BMF network and a set of people (professors and students) working in such space that wear a SPINE-based system. The main aim of the testbed is to evaluate the scalability and responsiveness of the developed system.

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