Integrating Wireless Body and Ambient Sensors into a Hybrid Femtocell Network for Home Monitoring

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***Abstract*—The current paper proposes a hybrid sensor network for indoor monitoring and discusses the way both body and ambient wireless sensors are integrated into this network. A multi-level system architecture is described which relays acquired data and alerts to relevant third parties. Its main purpose is to build a system that monitors the house of a patient and is capable of collecting data from all the nodes. The system contains ambient sensors that monitor temperature, humidity, pressure and light. Beside the ambient sensors, the network also contains body sensors situated on the patient that monitor different health parameters like temperature, heart rate and motion capture. Efficient correlation among the two data-sets can lead to rapid response in case of an emergency with a high degree of autonomy and independent living for the patient.**

Keywords: wireless sensor network, femtocell, hybrid, ambient sensors, body sensors.

I. INTRODUCTION

Home care for the elderly and chronic disease persons has become an economic and social necessity. According to the US Bureau of the Census, the number of old people (65 - 84 years old) is predicted to double from 35 million to 70 million by 2025 [1]. This trend shows that the world elderly population will double from 375 million in 1990 to 761 million in 2025. Furthermore, overall healthcare expenditure in the US was $1.8 trillion in 2004, and this number is projected to be triple by 2020, or 20% of the US Gross Domestic Product (GDP) [2].

The latest discoveries in wireless communications, intelligent low power sensors and integrated circuits made possible the creation of Wireless Body Area Networks (WBAN). A WBAN can be defined as a collection of low power, miniaturized, lightweight wireless sensor nodes that monitor the human body functions and the ambient environment. Also, WBANs have a lot of innovative and interesting applications in different domains, such as healthcare, entertainment or military [3].

Because of demonstrated need and market demand, WBAN research has concentrated on healthcare applications, addressing the weaknesses of traditional patient data collection, such as imprecision (qualitative observation) and undersampling (infrequent assessment). In contrast, WBANs can continuously capture quantitative data from a variety of sensors for longer periods. By addressing challenges such as the energy-fidelity tradeoff, WBANs will enable telehealth applications - medicine beyond the confines of hospitals and clinics - and, because of their human-centricity, will facilitate highly personalized and individual care. WBANs integrated with higher-level infrastructure will likely excel in healthcare scenarios, serving the interests of multiple stakeholders. In addition to delay-insensitive applications such as longitudinal assessment, WBANs that can offer real-time sensing, processing, and control will augment and preserve body functions and human life. WBAN researchers are already working to improve deep brain stimulation, heart regulation, drug delivery or prosthetic actuation. WBAN technology will also help protect those exposed to potentially life-threatening environments, such as soldiers, first responders, and deep-sea and space explorers. Finally, WBANs are well positioned to benefit from the intersection of two formerly disparate application areas. Physiological and bio-kinetic sensing applications are increasing as athletes and fitness enthusiasts seek to improve human performance, while gaming systems are pushing their envelope by integrating more sophisticated interfaces based on human movement. With the crossing of these markets, WBANs are well positioned to deliver the biofeedback and interactivity necessary for next-generation fitness and entertainment applications.

The rest of the paper is structured as follows. Section 2 presents related work in the field of intelligent health systems employing body area networks. Section 3 is dedicated to the network model of the hybrid femtocell which includes the ambiental sensor network (ASN), the body sensor network (BSN) as well as the appropriate network interfaces for data distribution. The experimental set-up and results are highlighted in section 4 along with opportunities for complementary and cooperative sensor data fusion. Section 5 concludes the paper and exposes the directions for future work.

II. RELATED WORK

An early prototype of a mobile health service platform that was based on Body Area Networks was MobiHealth [4]. The authors described a comprehensive framework for mobile health services relying on dedicated sensors for vital parameter monitoring and a communication infrastructure over next generation public wireless networks.

An Internet based topology is proposed in [5] for the remote home monitoring applications that use a broker server, managed by a service provider. The security risks from the home PC are transferred to the broker server and removed, as the broker server is located between the remote monitoring devices and the patient's house.

The most important requirements of the developer for an e-health application are size and power consumption of the embedded computing and communication devices, as considered in [7]. At a higher hierarchical level, taking into account the data-driven nature of the deployed systems, suitable decision support algorithms and optimizations techniques must be implemented. Also, in [8], a comprehensive study of the energy conservation challenges in wireless sensor networks is carried out. The need for effective utilization of limited power resources is also emphasized, which becomes pre-eminent in wireless sensor networks.

III. Network Model

The current paper proposes an intelligent sensor network based on femtocells having two types of communication methods: low-power wireless comunication operating in unlicensed bands such as the 2.4 GHz Industrial, Scientific and Medical (ISM), and compatible fiber optic (Radio over Fiber - RoF). Depending on the use case, the low-power wireless can be implemented either by: IEEE 802.15.4/ZigBee or IEEE 802.15.1/Bluetooth technologies, revealing a trade-off between extensive node and network life-time and higher data throughput.

A femtocell contains two important layers: the body sensor network (BSN), the ambient sensor network (ASN), as presented in Figure 1. Each one performs a range of functions which include data acquisition and processing, storage and communication. The general gateway acts as a data concentrator and offers dedicated interfaces for the integration of the hybrid femtocell, as well as the link to the outside world, disseminating the information through the internet to authorized third parties. An additional feature is that multiple BSNs can operate inside a femtocell, they acount for different persons living in the same space and they are identified by unique network IDs.

The BSN has the following characteristics:

- battery-operated, easily rechargeable;
- ”friendly” mobile sensors, the sensors have to be small so that the patient is minimally disturbed upon wearing them;
- short-distance wireless radio communication;
- low power consumption, time between charges ranging from days to weeks;
- very low radiation, given the fact that the sensors are worn on the body, they should be compliant with current standards which set health realted specific absorbtion rates for radio emissions.

The ASN has the following characteristics:

- fixed sensors, placed optimally in order to maximize radio coverage with the least number of sensors;
- wireless communication, larger range than for the body sensors;
- multi-hop, mesh networking;
- low power consumption, small maintenance overhead, with the possibility of critical router nodes being mains powered.

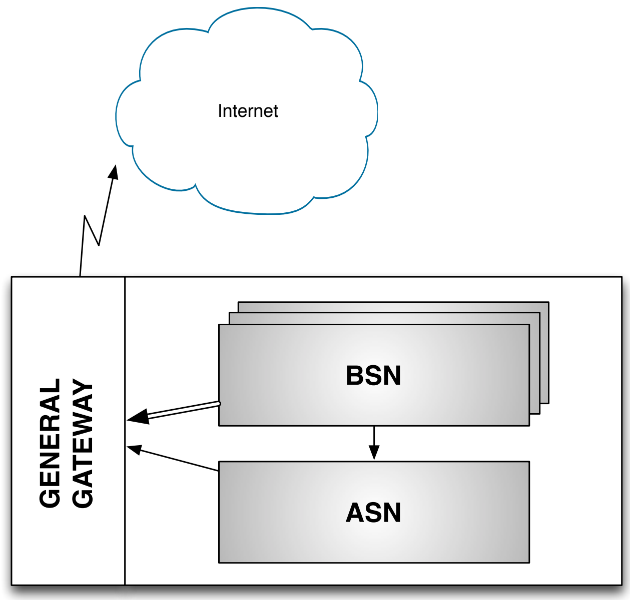


Fig. 1. Hybrid Femtocell Configuration

The body sensor network always interacts with the closest ambient sensor network. Therefore, if the patient is in the bedroom, then the BSN will interact with the ASN from the bedroom. If the patient moves in the living room, the communication of the BSN is done with the ASN from the living room, and so on. As a conclusion, the BSN always communicates with the closest ASN in its area.

A femtocell has to be activated only when its sensor is in the presence of the corresponding network. For this reason, every BSN is uniquely identified in order to manage effectively the switch from one ASN to another and the management of multiple BSNs by one ASN. The whole system of the wireless sensor network is composed of femtocells, every patient having its own femtocell.

Nodes are interconnected in different ways. The body sensors, part of the body sensor node (BSN), transmit their measurements to the Processing and Communication Unit - PCU, also part of BSN - over very short distance. BSN communicates wireless, via PCU, with the ambient sensor nodes over short distance (Short Distance Wireless communication SDW). Since ASN is in a fixed position relative to another ASN in the same house or even car, it communicates with these over RoF. SN communicates wireless with each other SN over long distance (Long Distance Wireless communication LDW) [9]. Figure 2 illustrates a multi-femtocell system architecture.

The goal of the system is to collect relevant data for reporting and processing. Therefore, the nodes should be able to communicate with each other so the system has a greater surface coverage. The main obstacle in designing an architecture for a indoor wireless sensor network is represented by thick walls, large metal objects and interfering devices, operating in the same frequency bands, because data packages are lost in the communication. For this reason, our solution

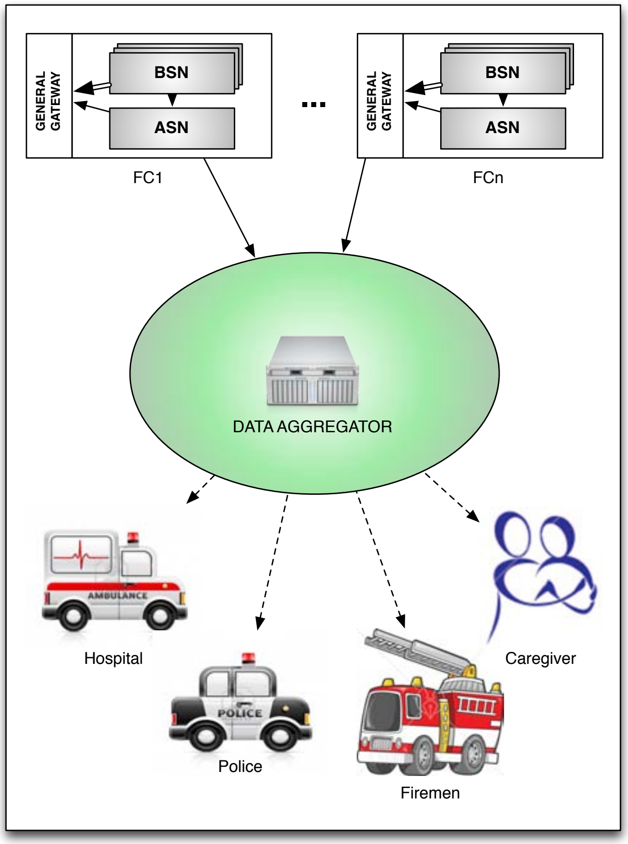


Fig. 2. Multi-femtocell System Architecture

is to have a communication using RoF where thick walls are in the way of the nodes, and wireless communication where there are no obstacles.

In case of an alert, the corresponding element from the system architecture is alerted and actions are taken. For example, if the femtocells send a burglary alert, then the police is noted. If smoke sensors become activated, the femtocell sends a fire alert, therefore the firemen are alerted, and so on.

Regarding sensor placement, the BSN is placed on the patient's body depending on the investigated parameters: motion, biometric signals, biosensors. The ASN consists of nodes which are assigned to each room of a housing unit. The network topology can easily be changed in order to meet the demands of the patient and the social worker can help him modify the position of the sensors. This is important because we don't need to have a sensor in every room, but only in those which are currently used. The only restrictions which have to be taken into account are those regarding the difficult nature of the indoor environment . This includes thick walls which may prove too massive for the signal to go through.

Our infrastructure also offers routing facilities, increasing the reliability of the network by self configuring into a multihop communication system whenever direct data sending to the gateway is not possible. This test case has been also taken into account during our experiments. Because of their small size, they can be easily concealed into the background, interfering as little as possible with the users day to day routine. We have also the possibility to set the sampling rate at a suitable level in order to achieve low power consumption and by this a long operating range without human intervention.

IV. Experimental Set-up and Results

In order to implement and validate our system, we design and experimental set-up as shown in Figure 3. It consists of a BSN designed for motion detection and electrocardiogram (ECG) monitoring with 3 nodes and an ASN for temperature, humidity, barometric pressure and light. In the proposed scenario, the ASN is considered a fixed, reference infrastructure with the BSN, attached to the patient's body, is globally mobile in the wireless communication coverage field of the ASN.

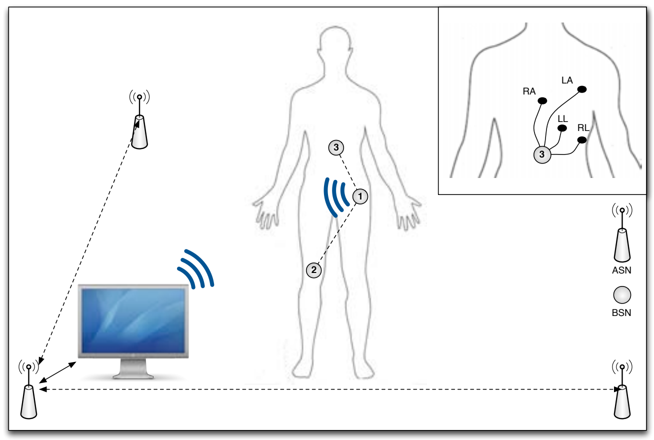
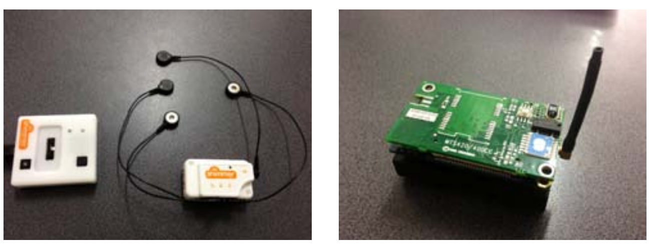


Fig. 3. Femtocell Implementation

The BSN is built around the Shimmer platform [10] which periodically samples biometric data from the patient. A Shimmer node is a modular embedded wearable device for body sensor network applications. It uses the Texas Instruments MSP430F1611 microcontroller with 8MHz clock speed, 10KB RAM and 48KB Flash memory. Two communication options are available: IEEE802.15.1/Bluetooth using the Roving Networks RN-42 circuit or IEEE802.15.4/ZigBee via the CC2420 radio transceiver. This allows flexibility in the design and commissioning of the BSN, where time sensitive data is sent via Bluetooth, which offers better response and higher throughput, whilst long-term monitoring of biometric data can be communicated using the lower powered link thus achieving longer battery lifetime. Other significant features are the built-in MicroSD card reader which opens up the possibility of local storage of data in the case of lost communication. Also, the node is provided with a 450mAh rechargeable Li-Ion battery which adds flexibility and a more compact form factor than when using standard AA or AAA 1.5V batteries. The structure is expandable with daughterboards for ECG, GSR, EMG and strain gauges, besides the integrated Freescale MMA7361 tri-axial accelerometer with 1.5g/6g measuring range.

The building block of the ASN is the IRIS platform, suitable for indoor monitoring [11], developed around the XM2110 main processing/radio board, which hosts an ATMega 1281 8 bit MCU and a IEEE 802.15.4 compliant RF230 radio transceiver operating in the 2.4GHz Industrial Scientific and Medical (ISM) band. This is the newest module in the line of the original Berkeley motes and is supported by the open-source community under TinyOS 1.x and 2.1 an event-based, low footprint operating system for resource constrained devices. Compared to the previous iteration MicaZ, the producer mentions better performance in terms of radio coverage and improved energy efficiency. The 51-pin connector provides stackable expansion possibilities to connect to the MCU peripherals.

The MTS400 board provides a series of sensors for: humidity and temperature, barometric pressure and temperature, light and 2-axis accelerometer. The Sensirion SHT11 humidity and temperature sensor offers 14-bit precision, humidity range of 0 to 100% with an accuracy of $\pm$ 3.5% and temperature range of -40° C to +80°C with a $\pm$ 2° C accuracy. The Intersema MS55ER measures atmospheric pressure between 300 and 1100 mbar with an accuracy of $\pm$ 3.5%. Finally, the TAOS TSL2500 digital sensor measures light in the spectrum from 400 to 1000 nm.



(a) (b)

Fig. 4. Building Blocks for the BSN and ASN (a) Shimmer Node with ECG Board (b) IRIS mote with MTS400 Sensor Board

ECG measures the electrical activity of the heart during a certain period. The output consists of an analog voltage time series which can be either directly interpreted or further processed. It is used in diagnosing acute and chronic conditions which cause irregular behaviour of the heart. The periodic signal presents the following features [12]:

- P wave: atrial depolarization, duration 80-100 ms;
- PR segment: AV nodal delay, duration 120-200 ms;
- QRS complex: ventricular depolarization (atria repolarizing simultaneously), duration 80-120 ms;
- ST segment: time during which ventricles are contracting and emptying, duration 70-80 ms;
- T wave: ventricular repolarization, duration 200 ms;
- TP interval: time which the ventricles are relaxing and filling.

We collect data from an ECG node with four leads: RA - right arm, LA - left arm, RL - right leg, LL - left leg. In order to be able to accurately evaluate the waveform, the sampling rate is set at 512Hz. Experiments have shown that using the maximum sample rate of 1024Hz and trying to simultaneously transmit the values results in a low packet reception rate. Using a peak detection algorithm we are able to detect QRS complexes in two phases. First, the local maxima of the time series are computed and then, by thresholding relative to the baseline obatining the desired values. Correctly identifying the R peaks and knowing the sample rate enables the computation the heart rate of the patient as in Figure 5.

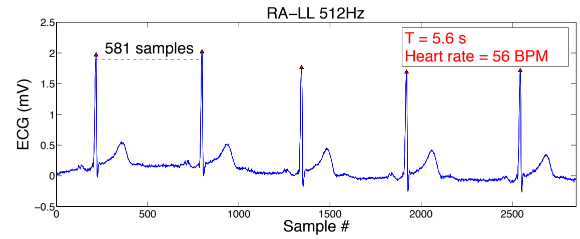
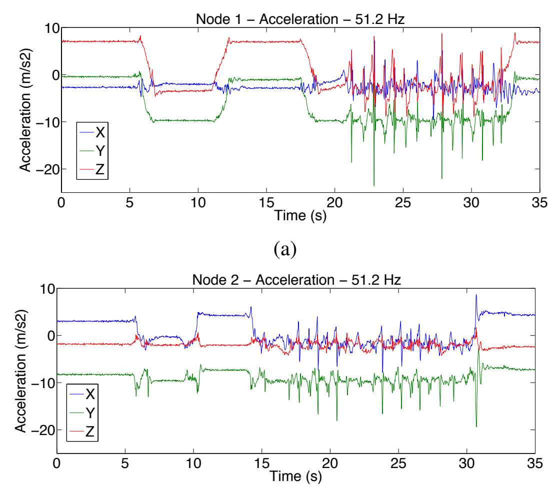


Fig. 5. Electrocardiogram Data

Acceleration information is supplied by the other two nodes which are placed on the left waist and above the right knee. Figure IV shows data collected during three types of activities: sitting, standing and walking about. An adequate sampling rate was set at 51.2 Hz. The first two activities are characterised mainly by the static values on each of the three axis. Walking can be evaluated by computing the main frequency components of the signal and its amplitude. We are also able to identify transitions between states.



(a)

(b)

Fig. 6. BSN Motion Capture (a) Right Leg (b) Waist

Root-mean-square (RMS) acceleration for each direction is computed. This is an useful statistical indicator for measurement which have both positive and negative values evaluates the energy of the given signal. For a single axis x, it can be expressed as:

$$x_{RMS} = \sqrt{1/n \sum_{1}^{n} x_i^2} \quad (1)$$

TABLE I
RMS ACCELERATION

Activity	Node 1 - Waist	Node 2 - Right leg
sitting	8.9715	7.5524
standing	9.8277	10.5229
walking about	10.3111	10.9741

Globally evaluating human activity in the time domain requires all three directions to be taken into account, evaluating the magnitude of the combined axis signals:

$$a = \sqrt{x_{RMS}^2 + y_{RMS}^2 + z_{RMS}^2} \quad (2)$$

In our case, global RMS values are listed in table I.

Using this approach the available data is divided into training, testing and validation data and fed to an intelligent pattern recognition algorithm able to discern the nature of the observed activity. While this approach is suitable for *sitting* and *standing*. In the case of the third type of activity, that we defined as *walking about*, frequency domain techniques give better results.

For ambiental monitoring we focus on data collection for temperature, humidity, barometric pressure and light. Nodes are configured in a low-power mode where they wake up, sample the sensors and transmit the measured values towards the base station. In this case data is collected every 10 seconds and time synchronization is handled at the routing layer of the mesh network. Time drift, which occurs mainly due to manufacturing inconsistencies and temperature effects on the crystal oscillators, is periodically compensated by the central coordinator of the network.

Circadian variations in temperature and humidity affect human well being in the case of healthy people but it becomes a primary concern in chronic conditions such as heart and respiratory diseases. Temperature variations over two days are shown in Figure 7. The differences among reported values for the three nodes are due to the placement of the devices around the house. Node 6692 is assigned to the kitchen, node 6782 to the living room, while node 1 is placed in the dormitory. One of the main concerns is also to assure optimal radio coverage with minimal amount of nodes.

Especially for cardiac related problems, the ambient pressure is a valuable indicator (Figure 8). Given the small area which the ASN is tasked to monitor, there should be no differences in the reported values. The variations which appear between are due to sensor errors and impact on temperature on the pressure sensitive element. To increase data quality, the three pressure - time series can be combined in order to average out the measurement error. Our system provides a wide range of historical data and can prove the correlation between the high and low points of ambient pressure and the monitored health parameters regarding blood pressure. This may provide the patient with the right medication whenever it is necessary predicting the oscillations before they start affecting the blood system.

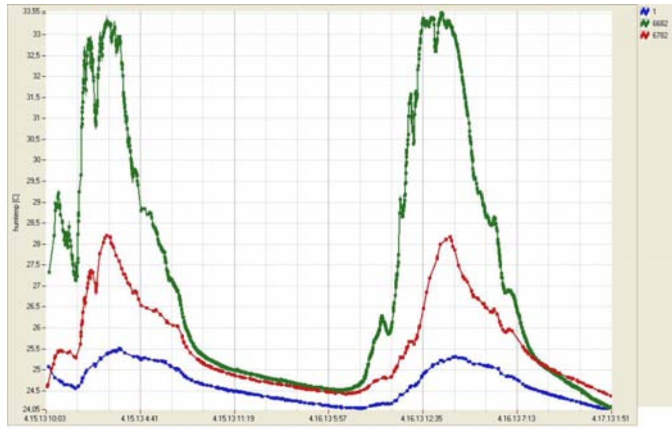


Fig. 7. Temperature

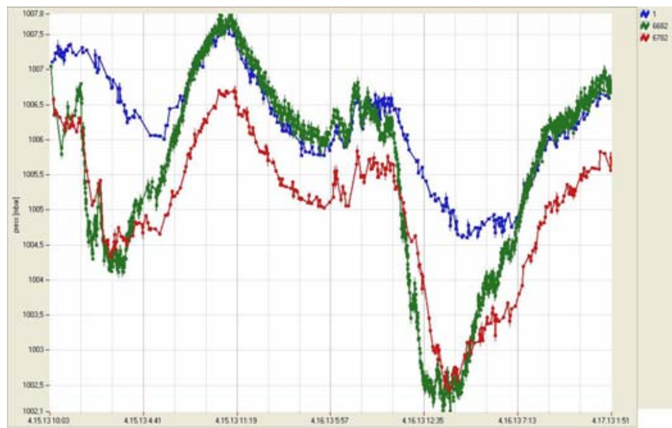


Fig. 8. Pressure

Ambient light (Figure 9) may give an indication over the hygiene inside the monitored space, being correlated with germ growth and even with mental diseases.

These values retrieved through the ASN sensors are important mostly during the cold season when they can be associated with germ infestations and mold propagation. Having all these data at their disposal, medical personal can give valuable advices preventing risk factors to accumulate and alter the health of the people living inside the monitored space. Table

TABLE II
AMBIENTAL DATA COLLECTION

ID	Time	Temp. [C]	Hum. [%]	Pr. [mbar]	Light [lux]
1	10:27:15	24.89	47.7	1007.1	74.25
6682	10:27:15	28.3	35.7	1006.4	1847.1
6782	10:27:16	25.4	40.9	1006.4	451.8
1	10:28:13	24.89	47.7	1007.1	74.25
6682	10:28:14	28.3	35.7	1006.4	1847.1
6782	10:28:15	25.4	40.9	1006.4	451.8
1	10:29:12	24.88	47.7	1007.1	74.25
6682	10:29:12	28.2	35.5	1006.3	1847.1
6782	10:29:12	25.6	40.8	1006.4	426.69

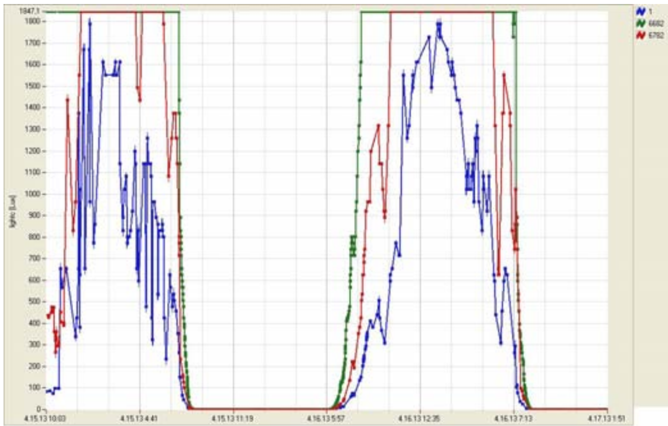


Fig. 9. Light

II highlights a sample of the data collected from the ASN. It includes: node ID, timestamp and the environmental parameters and associated measurement units. A separate log file keeps track of raw data packets transmitted inside the network. These are monitored using dedicated hardware, a radio sniffer for low-power wireless protocols, and give useful information concerning the behaviour of the routing layer of the network reacting in response to varying channel quality parameters supplied by the sensor node radio component (RSSI, LQI).

Together with the health monitoring sensors and the emergency sensors, the environmental sensor provide a complete picture over the everyday living space of the monitored person. The role of the environmental sensors is mostly prevention rather than acting actively as a trigger for day to day health preservation related actions.

Data aggregation is performed in three ways. First, at the local sensor network level in-network aggregation is performed with the goal of energy efficiency. Second, the gateway e.g. a PC with suitable middleware and client applications, of each femtocell assimilates the preprocessed information from the dedicated sensor networks in a localized decision structure. Finally, the information from multiple femtocells is consolidated at a higher hierachical level. This central aggregator is also responsible for the interaction and alerting of the responsible stakeholders that were previously mentioned: caregivers, ambulance, police, firemen.

V. Conclusion

As a conclusion, the current system architecture proposes integration of body and ambient wireless sensors into a smart hybrid sensor network for indoor monitoring using a multilayer femtocell. Two very important aspects were detailed in this paper, the ambient sensor component and the body sensor component one. Two experiments were carried out: the first covered the body sensors, in which three sensor nodes were placed strategically on the subject in order to determine different actions and measure biometric signals such as the ECG; the second one had as a main purpose to determine ambient parameters, like temperature, humidity, barometric pressure and ambient light.

Future development can be done by covering a higher variety of sensors, especially on the body part. For example, blood rate sensors could be vital in determining the current health status of a patient. In this way, with the help of an implemented system for notifications, an ambulance or a fire truck could come faster and save the life of the patient. Also, when collecting data using a wireless sensor network, missing sensor data is inevitable because of the inherent characteristics, causing great problems in all the applications. Therefore, in order to fix this problem, the data must be estimated very accurate, so one of the future developments is to apply an estimation algorithm that improves the quality of the harvested data from the sensors.

Acknowledgment

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