Evaluation of Wireless Body Area Sensor Placement for Mobility Support in Healthcare Monitoring Systems

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Abstract. We present a 2-tier wireless system for healthcare monitoring of convalescing patients in non-critical condition. A network of sensors adhered to the patient's body used for vital signs collection, and a portable coordinator device forms one tier, whereas a point-to-point link between the coordinator and a fixed access point forms the other tier. We implemented a simple but effective handoff protocol to support uninterrupted monitoring of mobile patients by employing sensor devices featuring limited radio range and low power usage that are amenable for home use. Our experiments reveal that the wrist location is the most favoured for data relaying at walking speeds, as compared to the shoulder, hip, and ankle locations. Additionally, we observed that using sensor nodes as temporary relays may reduce the packet loss rate down to 20% of the value measured when employing a single hop delivery scheme between the coordinator and the access points.

Keywords: Wireless Sensor Networks, Wireless Body Area Sensor Networks, Handoff, Performance Evaluation, Healthcare Monitoring.

1 Introduction

Wireless Body Area Sensor Networks (WBASNs) continue to draw significant interest as a subcategory of Wireless Sensor Networks (WSNs) that enable untethered vital signs monitoring of people with healthcare problems and/or some form of disability [1]. From the perspective of data communications, the majority of WBASN research deals with Physical Layer and Medium Access Control (MAC) particularities of IEEE 802.15.4 radio technology [2]. This IEEE standard has been widely adopted both in the industry and in the academia, as it provides an excellent scheme for implementing low-cost, low-power sensor devices. On the other hand, miscellaneous issues at the Network Layer and at the Control Plane observe only moderate research activity.

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Advances in the area of WBASN have a special significance, primarily because of their potential for improving the lives of convalescing patients by enabling health monitoring at home, instead of at a hospital [3], [4]. In addition, the economic incentives for making WBASNs practicable for both public and private sectors are also clear. In fact, public healthcare expenses around the world are expected to increase significantly due in good part to the rising population of the elderly, in contrast to a smaller population of younger, working-age people to cover these costs through taxation. This circumstance has been a matter of concern for many years now [5]. Therefore, researching novel technologies that help offset healthcare costs and elevate patients' quality of life becomes of paramount importance.

In this paper, we focus our attention on two particular aspects of a WBASN-based healthcare monitoring system. The first aspect stems from the fact that we consider WBASNs formed by devices that employ IEEE 802.15.4 radio technology in their communications interface, including a coordinator node designated to arbitrate network traffic. Given the nature of the application, this coordinator node forwards the collected sensor data to an external device (using the same radio technology) for subsequent assessment. A problem arises here in that the transmitter's radio range in sensor nodes and the coordinator is deliberately restrained to conserve battery power. Therefore, multiple, fixed Access Points (APs) are needed in a home setting to ensure that the patient(s) will always be in range of a device through which vital signs information can be forwarded. This circumstance requires incorporating a handoff process that enables uninterrupted communications when a person moves from the coverage area of one AP into another. However, existing research considers only WSNs, whereas WBASN-related provisions are lacking [6], [7].

A second issue arises also because of the same limited transmission power in the WBASN nodes, which has a direct impact on the received signal strength (RSS) at the APs when a person moves about his/her residence (i.e., similar to what occurs when a mobile phone user travels from one site to another). This circumstance can further aggravate if the location of the coordinator device on the patient's body (e.g., waist, ankle) is not beneficial for relaying data to any given AP. One simple solution is to have the coordinator employ one of the WBASN nodes as a temporary data relay in an attempt to improve the RSS at the AP. Therefore, it becomes important to investigate if and when this approach is suitable, especially since it may leverage the coverage area of APs around the house, translating into fewer hardware devices needed, and the corresponding money savings. We summarize the contributions of this paper as follows:

1. We describe the protocol design for the WBASN handoff process by employing distinct radio channels to leverage system capacity in a multi-user setting.
2. We describe the protocol design used by a WBASN coordinator for finding a sensor that can relay data onto a fixed AP.
3. We present the results in terms of packet loss and coverage area of a 2-tier system implementation with actual sensor devices, including variations in the coordinator and sensors' positions on a person's body, and their use as relays.
4. We discuss practical experiences observed during performance evaluations, which can serve as preliminary indicators that can be referenced during the subsequent design of systems with a similar architecture.

The rest of this paper is structured as follows. Section 2 lays down the design foundations and rationale of the system that we evaluate. Section 3 explains in detail the protocol design for WBASN handoff and data, as well as the signal smoothing techniques tested. Section 4 presents the experiments' setup and performance evaluations results. Section 5 provides a discussion of the evaluations and of our practical experiences and observations, and Section 6 concludes this paper.

2 Foundations and Design Rationale

In this section, we describe the working assumptions and foundations for the wireless elements of an end-to-end health monitoring system. We adhere to the WBASN concept of having one or more convalescing patients individually wearing a number of sensors on their bodies in order to collect relevant information needed to determine their current health status. In its simplest form, a portable coordinator device collects vital signs readings from the WBASN, and forwards them through a fixed AP to a data processor where it is pre-analyzed (i.e., in a multi-tier fashion [8]). Detection of a health-related anomaly according to the embedded algorithms triggers a communications session with a remote monitoring station, whereby qualified personnel make a more accurate assessment, as depicted in Fig. 1. The proposed system can be deployed in a regular home or in a nursing home for the elderly, allowing a number of patients to be concurrently monitored in real-time at a single station. In that case, a condition assessment station could be placed locally in order to respond quickly to emergency situations (shown as a shadowed element in Fig. 1.)

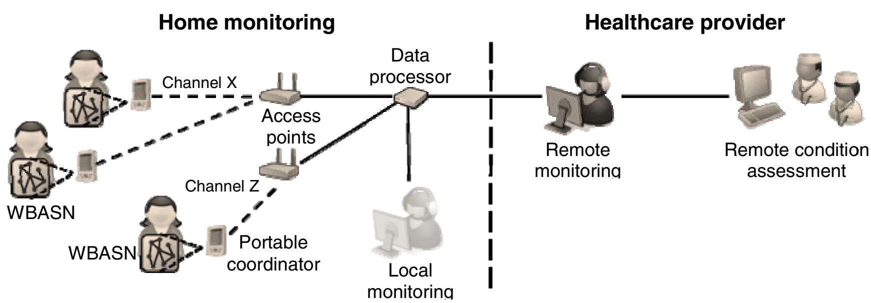

Fig. 1. Depiction of a healthcare monitoring system of convalescing patients at home based on WBASNs and multiple channel usage for improving system capacity.

The main advantage of incorporating a WBASN into the monitoring system is that it allows patients to move freely in their living quarters without wearing wires, as otherwise required by existing commercial products (e.g. [9]). However, this improved, wireless approach requires several considerations to make it practicable. From a data communications perspective, it is clear that data link utilization could become a problem if multiple users require that their Electrocardiographic (ECG) signal be transmitted. Though the IEEE 802.15.4 standard stipulates a baseline data rate of 250 Kbits/sec, in practice this value degrades significantly. This can be easily inferred by the following analysis for a non-beacon enabled MAC scheme.

Considering that the maximum packet size (*MAC-level protocol data units* or *MPDU*) is limited to 127 bytes (of which 114 bytes at most are user-defined, as per a 13-byte minimum overhead at the MAC layer), and adding 6 extra bytes of overhead (due to the Start of Frame Delimiter [SHR], and Frame Length [PHR]), the transmission delay of a full frame at the Physical Layer yields: $[(127 + 5 + 1) \times 8] / (250 \times 10^3) =$ 4.256 mS.

It is also desirable that packets be acknowledged between WBASN devices. Since ACK frames occupy 11 bytes, at 250 Kbits/sec, an ACK frame transmission takes an additional 0.352 mS. Adding the two previous values to a 0.192 mS turnaround delay reserved for the radio to switch from receiving to transmitting mode, and to a predefined 2.368 mS delay ascribed to the CSMA/CA channel access time (with a default backoff exponent of 3) equals to 7.168 mS. Dividing the 114 bytes defined for user payload by this number yields a maximum data rate of 127.2 Kbits/sec, although a much higher packet error rate can be observed for a non-beacon enabled MAC scheme. Moreover, in a multiple user, star-topology scenario, the actual channel utilization degrades significantly as seen in a typical Aloha network, even though more optimistic values obtained through computer simulations have been reported [10]. Given these circumstances, a WBASN-based, ECG monitoring system operating at a minimum sampling rate of 250 Hz [11] in a room with just a handful of patients may become altogether ineffective.

In addition to the previous analysis, it is also evident that using a WBASN to continuously transmit vital signs data would most certainly drain the battery of its forming devices, thus defeating the very purpose of the low-power, low-data-rate IEEE 802.14.5 radio scheme. As a result, we argue that a WBASN should be used for healthcare monitoring of patients in non-critical condition that predominantly require follow-up treatment, or for people that otherwise require some form of limited monitoring. Under this assumption, patients' health can still be permanently monitored by the WBASN hardware, whereas a vital signs digest data can be sporadically forwarded by the corresponding coordinator in order to save bandwidth and battery power. To this effect, a data digest implies that only statistics and overall trends need to be transmitted in compact packets, though counter-arguments exist [8].

We also note that the limited radio range constraint of IEEE 802.15.4 radios can be used to the system's advantage, so that multiple users can be concurrently monitored at different sites without interfering with each other if each AP is assigned one of the 16 channels available in the 2.4 GHz band, as depicted in Fig. 1. In fact, assuming reduced co-channel interference, and using a strategic channel allocation scheme, a single cell can employ one of the 16 channels for communications between the WBASN coordinator and the AP, whereas the remaining 15 channels can be used for intra-WBASN communications (i.e., one channel per WBASN). Finally, it is evident that the Received Signal Strength Indicator (RSSI) at the APs will be highly variable when users move around. Therefore, we implement and test the performance of three types of filters in order to smooth out the RSSI values acquired through the radio interface of the APs and reduce handoff decision uncertainty. It is evident that the algorithms that implement these filters need to be highly efficient due to the severe hardware constraints found in WBASN coordinators and in cost-efficient APs. We investigate how this RSSI value estimation can be employed to initiate the process of finding a data relay for a WBASN, or to initiate a handoff process.

3 Protocol Design for WBASN Handoff and Data Relay Setup

In this section, we explain the signalling process that enables a WBASN coordinator to associate with any given AP within the system's deployment setting. We describe the corresponding protocols for a coordinator's association process to an AP, a coordinator/WBASN handoff process from one AP to another, and a relay assessment process that may help reduce the number of lost packets, as explained before.

3.1 Device Association and Handoff Protocol

We implemented a 4-way protocol that a WBASN coordinator device follows when first associating with an AP immediately after powering-up, or after a handoff command is received. However, a preliminary step is required to enable a coordinator discover APs within radio range. Since each AP in a deployment setting operates in a different channel, a coordinator scans all the 16 available by issuing a PING_MSG packet to the device with address 0 (pre-assigned to all APs) in each channel. In addition, all devices in the system are programmed to immediately return an ACK packet for every packet received at their radio interface. Therefore, when a coordinator receives the corresponding ACK for the PING_MSG packet issued, it first records its instantaneous RSSI value, and then tunes into the next channel *n* to conduct the same AP discovery process, as illustrated in Fig. 2.

It follows that once the initial discovery phase completes, the coordinator might have registered more than one ACK reply, and so it chooses to associate with the AP that yielded the highest instantaneous RSSI value. At this point, the coordinator issues an ASOC_RQST packet to the respective AP, and waits for the corresponding ACK signal. APs maintain a simple registry for each of the coordinator devices being managed, including a *state* variable that describes their current association level, which is updated as needed. After an association request is received and an ACK signal is automatically issued, the AP continues the process by sending an ASOC_RPLY packet that conveys the operating parameters that the coordinator will employ (e.g., its WBASN channel, check-in period, etc.). The reason for issuing an ASOC_RPLY packet separate from the ACK packet (instead of merging them) obeys to predefined directives of the IEEE 802.15.4 standard. Finally, the coordinator enters the CONNECTED state immediately after issuing the corresponding ACK for the ASOC_RPLY packet received. At this point, periodic DATA_MSG packet transmissions of the patient's vital signs information take place.

The RSSI from a WBASN coordinator's transmissions remains relatively stable at the AP as long as the patient remains stationary. However, this value decays rapidly as soon as s/he begins to move away from the coverage area of its current AP. When the RSSI value decays to a certain threshold, the AP issues a HNDF_CMD packet to the WBASN coordinator to initiate the handoff process, as depicted in the middle section of Fig. 2. At this point, it can be seen that the coordinator repeats the initial association process followed during power-up, leading to its association to a new AP located within proximity. Once the WBASN coordinator associates with a new AP, it switches back to its previous operating frequency and issues a FOLLOW_ME command instructing the sensors to retune their radios to the new AP's channel.

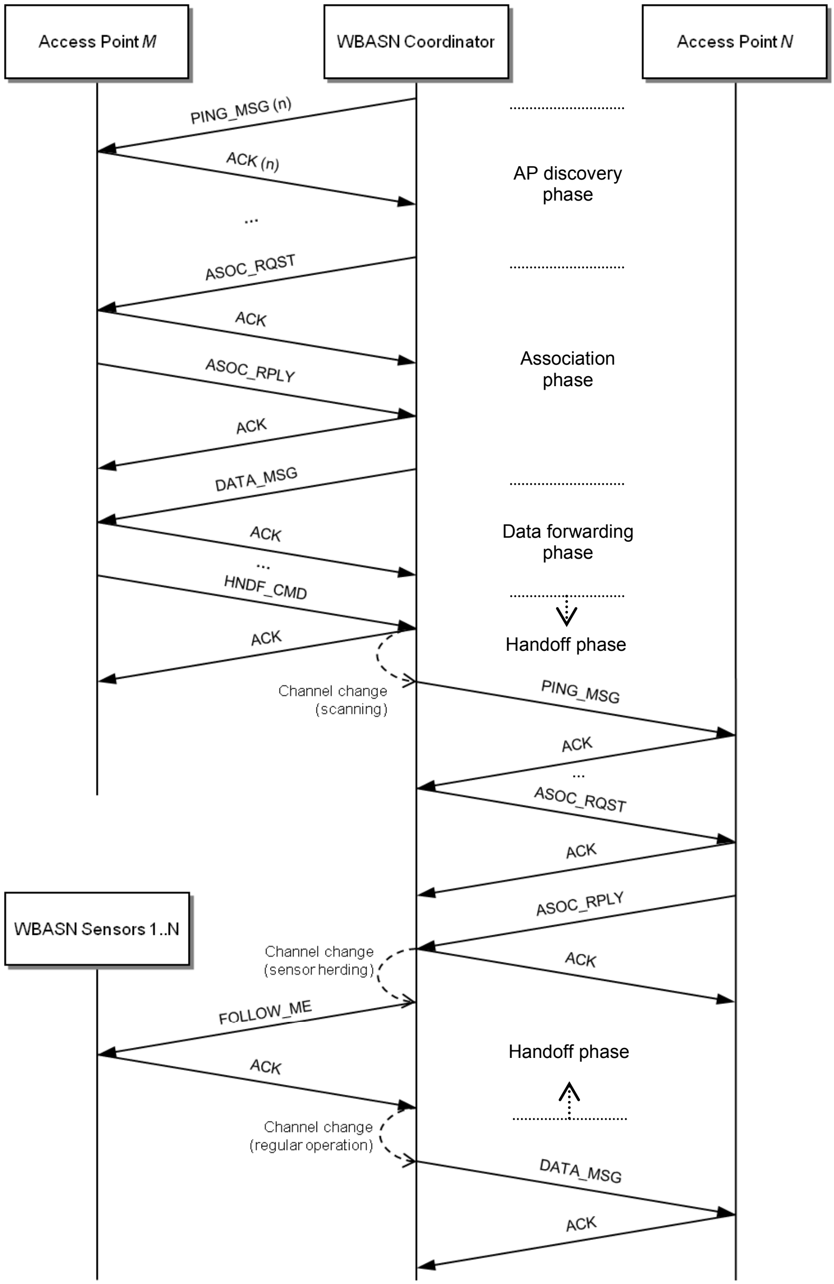

Fig. 2. Signalling protocol for the (re)association and handoff process between a WBASN Coordinator and Access Points, including sensors' retuning their radios into a new channel.

We refer to the WBASN's channel retuning as "sensor herding", whereby the coordinator momentarily switches to the old (but sill in-use) channel to communicate the new WBASN and AP-coordinator link channels, respectively. It can be inferred that sensors associate with their coordinator at power-up, and they operate in the same channel until the coordinator actively herds them into a new one. This process is necessary because the new AP might instruct the use of a new channel for intra-WBASN communications in its managed sector, as mentioned in Section 2.

3.2 Relay Assessment Process

As mentioned before, a patient's vital signs digest is continuously forwarded to the AP for as long as the RSSI value of the corresponding DATA_MSG packet remains above a predefined threshold. However, the system may attempt to leverage the RSSI value observed at the AP by instructing the coordinator to forward the DATA_MSG packet through a WBASN node that yields a higher RSSI due to its placement in the patient's body and its current orientation. Once again, if the RSSI value decays to a warning threshold value, the relay assessment protocol depicted in Fig. 3 initiates.

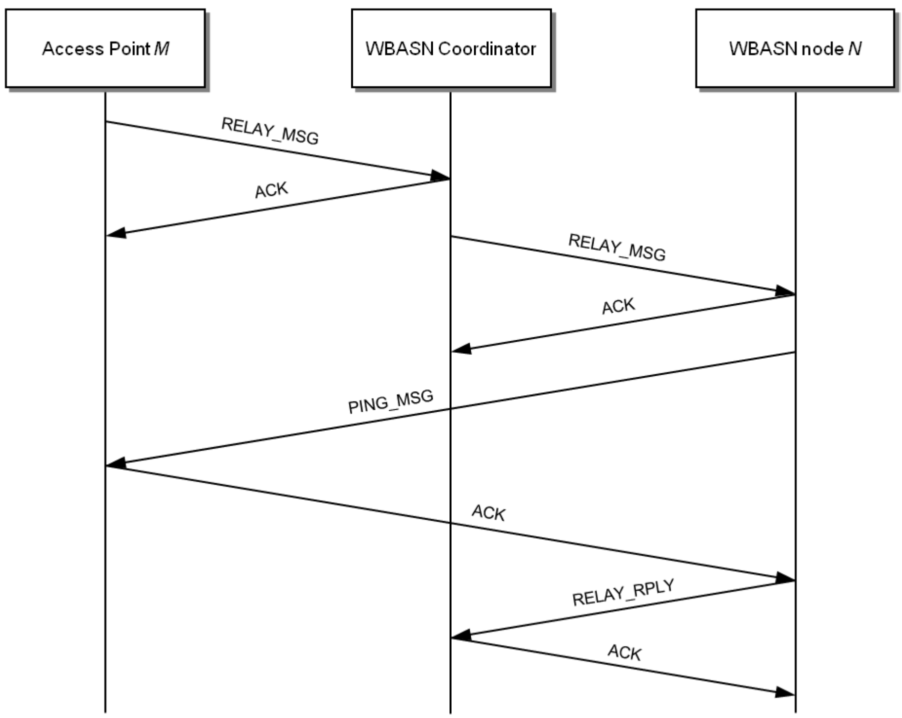

Fig. 3. Signalling protocol employed to determine whether there is a sensor node with a better RSSI value reading that can relay packets to the Access Point

The process begins by an AP's sending a RELAY_MSG packet to the WBASN coordinator from which the decaying RSSI signal was received. The coordinator might be unable to get the WBASN devices involved in the process immediately since they may be operating in low-power mode, which often includes turning off their radios for certain periods of time. When the coordinator deems that the sensors have (temporarily) re-enabled their radios, it forwards the RELAY_MSG packet onto them. At this point, each sensor individually issues a PING_MSG packet to the AP in order to obtain an instantaneous RSSI reading from the corresponding ACK signal. Then, each sensor replies with a RELAY_RPLY packet containing this value back to the WBASN coordinator, which keeps the identity of the sensor that observed a RSSI value over the warning threshold. A successful outcome indicates that at least one of the sensors yielded a better RSSI reading that can be employed to relay communications to the AP. When the next DATA_MSG packet transmission is due, the coordinator simply forwards it to the sensor node that was chosen as data relay, whereas the rest of the sensors can go back to low-power state.

The relayed data operation mode can be maintained so long as it provides the best means to maintain a more reliable communication session between the AP and the coordinator (since a low RSSI is a good indicator of a higher probability of having packet errors). It is inferred that the relay node's low-power duty cycle would need to be modified, so as to participate in both WBASN communications, and as a relay. If the patient is not moving, then the respective sensor will only enter the relay mode occasionally. However, when a patient moves, the RSSI value at the AP might fall once again below a warning threshold. When this happens, the relay assessment process is carried out again, thus providing a "fall-back" mechanism whereby the WBASN coordinator's transmissions might yield a better RSSI reading than before, so that the relay sensor's role is relinquished, and direct coordinator-to-AP communications resume. This process can be repeated as necessary until a patient moves far enough from the current AP's, and the received RSSI value (either with the coordinator or with any sensor nodes acting as relay) no longer stays above the warning threshold level. At this point, the direct coordinator-AP link is kept until a handoff command is received and the corresponding process executes.

3.3 RSSI Estimation at the Access Point

We have described the protocol design for association, handoff, and relaying of WBASN devices and APs. As explained before, all of these processes are triggered by the AP when the RSSI value of a coordinator or a relay device fall below either a warning, or a handoff threshold. However, it is a well known fact that RSSI values can vary unpredictably and significantly from one reading to another, especially when a person carrying a radio device moves. IEEE 802.15.4 radio is not immune to this problem [12], and the propagation effects introduced by a person's body are currently being explored [13]. In our case, the handoff and relay assessment processes can be visibly affected by highly-variable RSSI values at the device's receivers. Nonetheless, by applying one of several existing filtering techniques, we can obtain a smoothed sequence of RSSI values that can be separately referenced at distinct time periods for making both relay-use assessment, and handoff decisions [14]. In particular, we look at filtering techniques whose algorithmic complexity is amenable to resource-constrained devices, and ignore other salient techniques that impose a prohibitively-high computation cost (e.g., particle filtering).

Simple Moving Average. This is the simplest technique considered in our approach, whereby the summation of a sequence of values is divided over the number of samples k to obtain an averaged value, as depicted in the next expression:

$$\varepsilon_t = \frac{v_t + v_{t-1} + v_{t-2} + \cdots + v_{t-n+1}}{k} = \frac{1}{k}\sum_{m=0}^{k-1} v_{t-m} \quad (1)$$

The RSSI values v employed in the equation are time dependent, as indicated by the subscript t, and the oldest value is always replaced by the newest one in a shifting fashion. Evidently, a small k value yields an irregular output sequence that is more susceptible to large variations in either of its inputs. Conversely, a larger k value is more immune to large value variations whose effect is shifted a number time steps into future readings.

Discrete Kalman. The Kalman filter is one of the most popular and studied filters in signal processing that can yield remarkably accurate results. Its performance has already been evaluated for the case of device handoff in IEEE 802.11 networks [15]. One of the different forms commonly employed to represent the Kalman filter is:

$$\hat{x}_k^- = \mathbf{A}\hat{x}_{k-1} + \mathbf{B}u_{k-1} \quad (2)$$

$$P_k^- = \mathbf{A}P_{k-1}\mathbf{A}^T + \mathbf{Q} \quad (3)$$

$$K_k = P_k^- \boldsymbol{H}^T * (HP_k^- \boldsymbol{H}^T + \boldsymbol{R})^{-1} \quad (4)$$

$$\hat{x}_k = \hat{x}_k^- + K_k * (z_k - \mathbf{H}\hat{x}_k^-) \quad (5)$$

$$P_k = (I - K_k\boldsymbol{H})P_k^- \quad (6)$$

The Kalman Filter comprises two time-update equations (2), (3), and three measurement update equations (4) - (6). These values are iteratively computed at each time step during RSSI packet measurement, where **A**, **B** and **H** represent the n × n state transition matrix, the 1 × n control input matrix for a particular state x, and the m × n matrix relating to the state of the measurement, respectively. Additionally, **Q** and **R** represent the process and measurement noise covariance matrices, respectively. Finally, K represents the Kalman gain, $\hat{x}$ the state estimate, P the covariance estimate, and u the value for the control input. Assuming a stationary RSSI value when a patient is static, the matrices **A, H** are set to 1, **B** = 0 (because there is no control signal), and the subscript k is dropped, which greatly simplifies these equations.

Exponential Smoothing. This filtering technique is conceptually much simpler than the Kalman filter, and yields values that become weighted averages of future computations. Unlike the Kalman Filter that sports a time-varying gain that adjusts the respective weighs applied to new values, the exponential smoothing approach applies the same weigh to each new value, and does not rely on matrices, making it computationally undemanding. Similarly, the weigh value α used in the corresponding exponential smoothing equation determines the degree of autocorrelation, and thus the effect of large input value fluctuations, as well as the time shifting observed for the output signal:

$$\varepsilon_t = \alpha v_{t-1} + (1-\alpha) \times \varepsilon_{t-1} = \varepsilon_{t-1} \times \alpha(v_{t-1} - \varepsilon_{t-1}) \quad (7)$$

4 Practical Evaluation Setup and Results

4.1 Experiment Setup

Here, we describe the setup for the practical evaluation of our system with actual sensor devices. Though some practical implementations and WBASN experimentations have been reported before (e.g., [16]), outcomes of handoff, sensor placement, and data relaying tests are yet to be reported. We coded the corresponding protocols using the TinyOS (ver. 2.1) platform [17], and employed TelosB sensor nodes [18] to emulate the WBASN operation. We deployed 2 APs: one using a MIB600 board, and another using a MIB510 board, both of which had a Micaz node as their radio interface. A total of four sensors were secured around the body of test subject as shown on the left of Fig. 4.

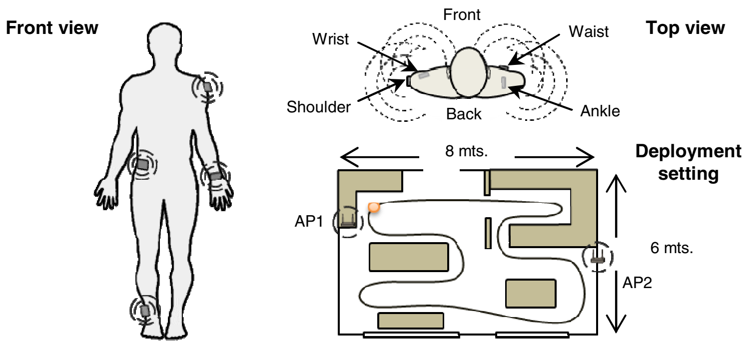

Fig. 4. View of the sensor's placement on a subject for the experimentation of our proposed system. The figure on the left shows a full-front body perspective. The figure on the upper-right shows a view from top that depicts the anticipated direction from the sensor radio beams. The figure on the lower-right shows the walking cycle followed during the testing of our system, and the Access Points' placement. The dot indicates the start, and cycle turn-around point.

The placement of the sensors obeys to the following rationale. The shoulder area is a highly plausible spot for placing a sensor on patients having their ECG signal monitored. Wrist placement is a natural choice because of the number of people who already wear a battery-powered timepiece. The hip/waist area can be considered an area in which a WBASN coordinator with larger batteries can be placed without causing significant discomfort to a person. Finally, the ankle area has been proposed by other WBASN researchers as a plausible spot to place an accelerometer sensor to detect a patient's movement or current activity. It is evident that this sensor placement scheme has a good potential to beaming radio waves particularly to the front and to the sides of an individual, as seen in the upper-right sketch of Fig. 4. (The wrist and ankle sensors appear shadowed since they are hidden from a top view perspective).

Because our system is intended for healthcare monitoring at home, we decided to run our experiments in an actual department dwelling, instead of at a computer lab.

A sketch of the setting appears in the lower-right section of Fig. 4. Experiments were run by having our tests' subject walk at two different speeds: 0.5 m/s, and 1.0 m/s, which we deem as reasonable walking paces for convalescing people at home. In order to gauge the number of lost packets and the utilization of the sensor nodes when assuming the role of data relays, the placement of the WBASN coordinator was cycled through the available positions (i.e., shoulder, wrist, hip, and ankle). Measurements were taken by having our test subject complete the walking cycle shown in the deployment setting sketch of Fig. 4 20 times – 10 times in each direction to eliminate bias in the results by exposing the WBASN devices to the inner and outer planes of the deployment setting. Otherwise, sensors would be exposed to the effects of indoors multi-path fading observed by walking in a single direction, but not from the corresponding effects observed by walking in the reverse direction. At 0.5 m/s, the walking cycle completes in approximately 1 minute, and at 1.0 m/s, in ½-minute. All nodes transmit packets with the full power available at their radio interfaces (0 dbm). For simplicity, the WBASN coordinator is always set to communicate with the respective AP once per second. All performance measurements collected by the APs are sent to a PC for subsequent processing.

4.2 Experiment Results

Our first tests were run to verify the correct system's operation, and the behaviour of the RSSI filters implemented. Fig. 5 shows sample plots for each the two walking speeds considered. Both raw and filtered signals are depicted for every one of the 3 algorithms described in Section 4 after a single walking cycle when only AP1 was active and no sensors were used, other than the coordinator node placed at the hip level. Fig. 5 (a) and (b) shows sample plots after using the Simple Moving Average algorithm that implements equation (1), which computes the outcome from 10 raw RSSI values collected. The number of chosen samples significantly reduces the magnitude of the variations seen in the RSSI readings, but the filtered sequence is displaced in time to some extent. At 0.5 m/s, AP1 is able to sample a larger number of RSSI values depicting magnitude variations of up to ±20 dBm from one reading to the next, evidencing the presence of a fast-fading channel as observed by the IEEE 802.15.4 radio interface. Conversely, the coarser granularity of a RSSI sample/meter at 1.0 m/s yields readings that omit smaller variations from one value to the next.

Fig. 5 (c) and (d) shows the corresponding plots for the Discrete Kalman algorithm with arbitrarily chosen parameters Q = 0.5, and R = 5. Whereas the sample plot for the 0.5 m/s walking speed shows no evident superiority of this algorithm over the Simple Moving Average, a detailed visual inspection of the 1.0 m/s case shows that Discrete Kalman filtering shows better performance in terms of a smaller response to larger variations in the raw RSSI readings, an output value that is less affected by previous variations, and thus higher stability during small variations from one sample to another. However, it is also evident that the effectiveness of the Discrete Kalman algorithm is not being fully exploited here because of the simplification in the values for the state transition matrices **A** and **H,** as explained before. Otherwise, distinct transition matrices would be needed for each motion case.

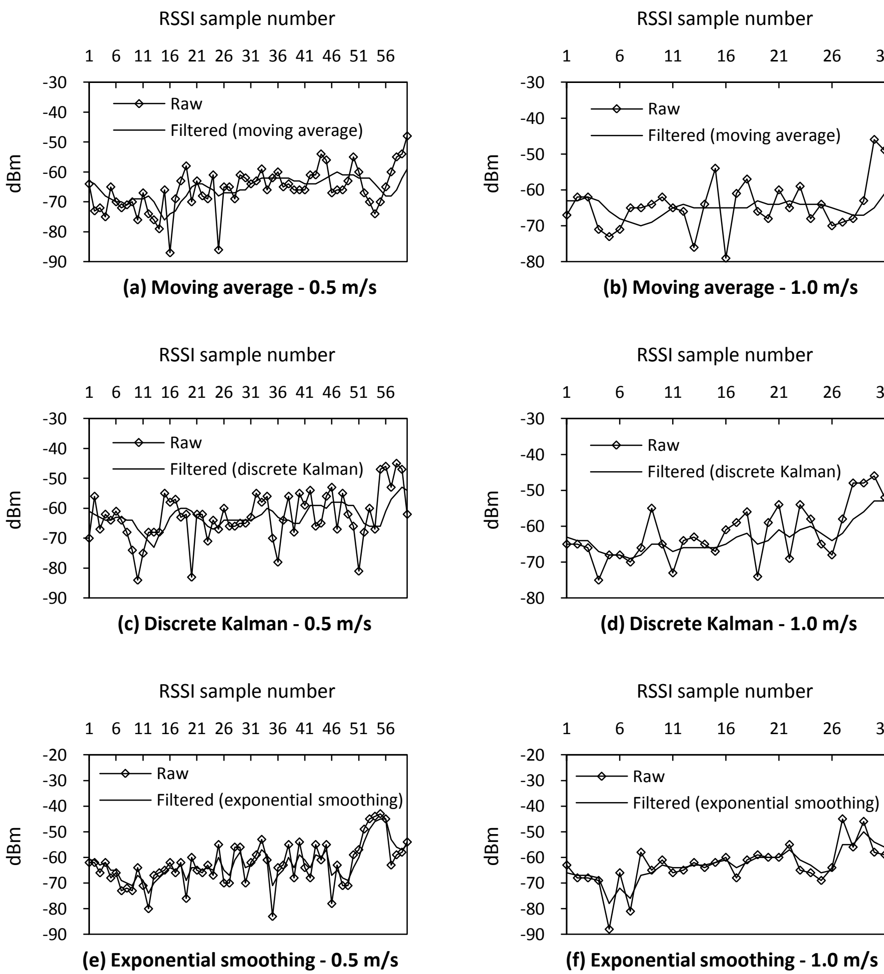

Fig. 5. Sample performance of three RSSI filters at an Access Point: (a), (b) – Moving average with 10 sampled values; (c), (d) – Discrete Kalman with Q = 0.5, R = 5; (e), (f) – Exponential smoothing with α = 0.5. Raw RSSI plots show markers.

Fig. 5 (c) and (d) shows the corresponding plots for the Exponential Smoothing filtering algorithm with α = 0.5. This value was purposefully chosen to obtain a more irregular signal. Here, the resulting sequence shows negligible time lag and more susceptibility to larger variations in the raw RSSI values. However, the filter is still able to discriminate large variations. Additional test runs with a smaller value for α (e.g., 0.1) yielded a filtered output very similar to the Discrete Kalman case, except that the Exponential Smoothing algorithm is computationally more efficient. This is an important consideration because the division operation in the Microcontroller Unit chip of the TelosB sensor nodes is implemented in software, which has longer execution times, and increased power consumption implications.

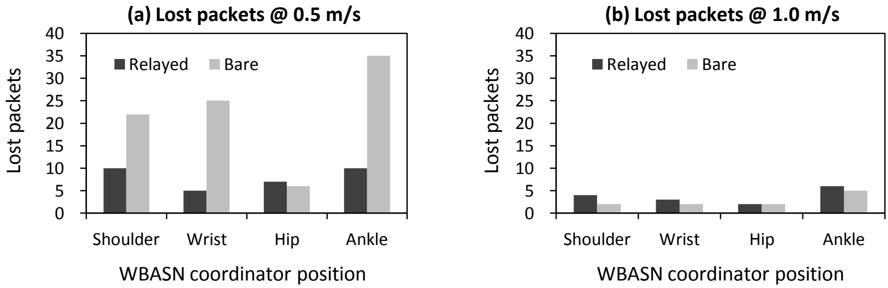

Fig. 6. Lost packet performance at: (a) 0.5 m/s, and (b) 1.0 m/s using relayed and bare (coordinator only) WBASN transmissions. The Exponential Smoothing filtering technique was used to estimate RSSI values.

Fig. 6 (a) and (b) depict the number of lost packets as measured by the two APs for the respective walking speeds after the full 20-round walking cycle is completed, as explained in Section 5 (10 cycles in each direction), and all sensor nodes are used. We decided to employ Exponential Smoothing filtering at the APs with α = 0.5. We explicitly chose this parameter's value for two reasons. First, we wanted that the system to purposefully experience moderate variations in the magnitude of filtered RSSI values, and force it into entering the relay assessment process relatively often once the filtered values hovered around the warning threshold set at -60 dbm. However, the filtered signal should not respond to large variations in raw RSSI values so as to avoid triggering an unnecessarily high number handoff processes that occur when the -70 dbm threshold is crossed. We can see from the 0.5 m/s walking speed tests that, except for case when the WBASN coordinator is placed at the hip/waist level, using sensors as temporary data relays yielded fewer packets lost. In this regard, packet loss was reduced from a 2-fold value in the coordinator-at-the-shoulder case, up to a 5-fold value in the coordinator-at-the-ankle case. The latter case is not surprising, since radio transmissions from a coordinator placed at the ankle (i.e., almost at ground level) can be expected to be decidedly more susceptible to a poor signal reception. However, we consider surprising that fact that using sensors as data relays at a 1.0 m/s walking speed yielded no benefits. Since the actual number of lost packets as observed in both cases barely differs by 1 or 2 (i.e., using sensors vs. using no sensors for data relaying), we deem that there is no significant advantage from one case to another, and so their performance is equivalent.

Fig. 7 and Fig. 8 illustrate the data relaying utilization of each sensor as a function of their placement for each of the 4 positions being considered for walking speeds of 0.5 and 1.0 m/s, respectively. For example, after completing the 20-cycle walk at 0.5 m/s and with the WBASN coordinator sensor placed at the shoulder, its utilization as the sole data transmitter spans 61% of the time, whereas the wrist, hip and ankle sensors are utilized 28%, 6% and 5% of the time, respectively, as shown in Fig. 7 (a), as per the combined results reported by both AP1 and AP2. We can also see that the WBASN coordinator always yields the larger utilization of the 4 sensors. On the other hand, the ankle sensor always has the lowest utilization among them all.

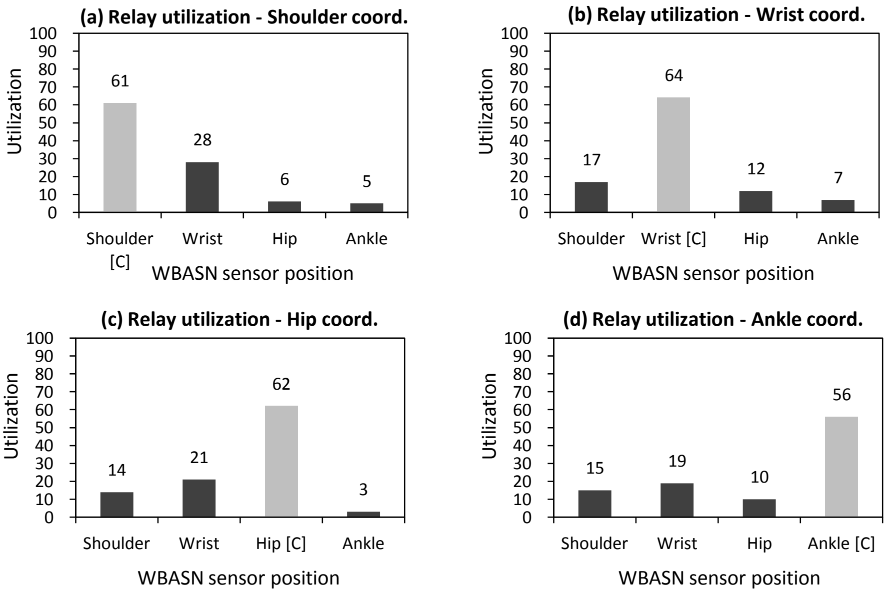

Fig. 7. Relay utilization at 0.5 m/s for each respective sensor and the corresponding coordinator position as described

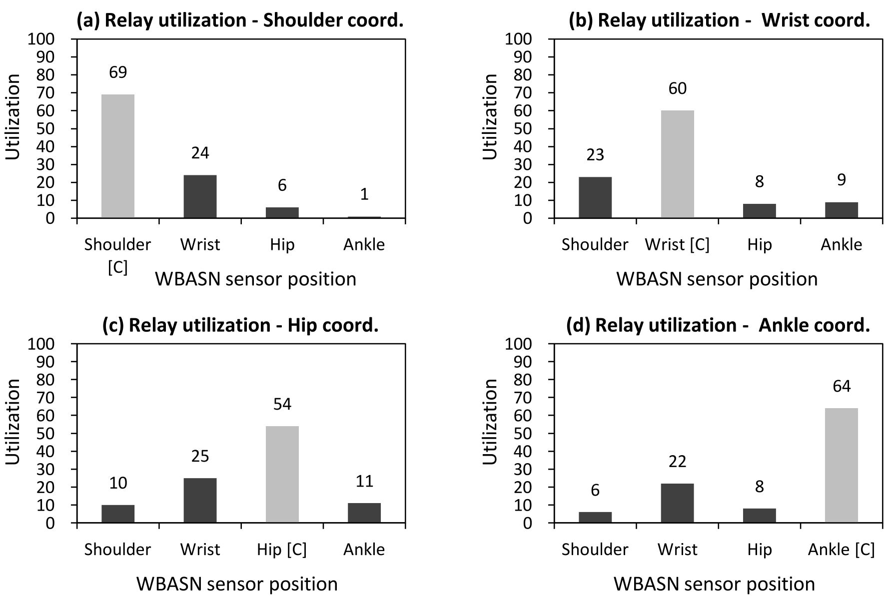

Fig. 8. Relay utilization at 1.0 m/s for each respective sensor and the corresponding coordinator position, as described

5 Discussion

We briefly elaborate on important aspects observed in the previous results. First, we expected to see a higher shoulder sensor utilization as a relay, since its position gave it an advantage over the rest of the sensors in situations where the latter would be blocked by different objects (e.g., furniture), whereas the former should benefit from a direct line-of-sight with either AP, except for a few cases. However, this was not the case, which brings us to the second observation: on average, the wrist sensor was the second-most utilized device as a relay, regardless of the coordinator's placement, the subject's walking speed, and the fact that the wrist experiences a 2-degree freedom of movement inherited from the patient's own displacement and his/her arm's inertial angular motion (though minor). Finally, the utilization of the coordinator in the ankle position as a percentage of the rest surpassed the one observed for the coordinator in the hip and wrist locations at 1.0 m/s walking speed, as evidenced in Fig. 8.

The previous observations have various implications. For instance, given that the wrist location favours the coordinator role of a device when walking at 0.5 m/s, placing a WBASN coordinator inside a timepiece would drain its battery quicker than the user would hope for, thus causing an inconvenience. However, this is not the case for a walking speed of 1.0 m/s. Additionally, our experiments depict results of a patient in motion from one home location to another only. Additional experiments (not reported in this paper) indicated that the coordinator's transmissions can degrade significantly even when a patient is static (e.g., while seating at a sofa watching TV). To deal with this type of issues, it can be reasonably argued that the coordinator might need to relay data through a different, off-WBASN device located near him/her, which motivates further research.

6 Conclusions

We designed and tested the performance of a handoff and data relay system that enables patient mobility for healthcare monitoring in home environments. Preliminary results indicate that using sensors in a WBASN on a temporary basis can help reduce the number of lost packets in certain circumstances. We learned that the actual placement of the WBASN coordinator has a direct effect on the system's performance, and that the wrist position was amply favoured for using as a temporary relay regardless of the patient's speed. Conversely, the sensor favoured with a line-of-sight to the access points does not necessarily yield the best reception. We believe that our investigations provide sufficient motivation for further research in this area.

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