Mobility Support for Health Monitoring at Home Using Wearable Sensors

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***Abstract*—We present a simple but effective handoff protocol that enables continuous monitoring of ambulatory patients at home by means of resource-limited sensors. Our proposed system implements a 2-tier network: one created by wearable sensors used for vital signs collection, and another by a point-to-point link established between the body sensor network coordinator device and a fixed access point (AP). Upon experiencing poor signal reception in the latter network tier when the patient moves, the AP may instruct the sensor network coordinator to forward vital signs data through one of the wearable sensor nodes acting as a temporary relay if the sensor-AP link has a stronger signal. Our practical implementation of the proposed scheme reveals that this relayed data operation decreases packet loss rate down to 20% of the value otherwise obtained when solely using the point-to-point, coordinator-AP link. In particular, the wrist location yields the best results over alternative body sensor positions when patients walk at a 0.5 m/s.**

***Index Terms*—Performance evaluation, pervasive healthcare, wireless body area sensor network (WBASN), wireless communications protocol.**

I. Introduction

Wireless body area sensor networks (WBASNs) have become one of the most promising technologies for enabling health monitoring at home. As a subcategory of the more general wireless sensor networks (WSNs), WBASNs facilitate the collection of vital signs in people with a health condition, and their subsequent transmissions to on/off-site locations for continuous monitoring [1]–[3]. As a result, patients in noncritical condition may be released from a hospital or clinic for at-home monitoring, once this technology is sufficiently mature. One major benefit introduced by WBASNs is that the lack of wires enables people to move freely in their residence while they recover, which is otherwise cumbersome to achieve with existing health monitoring technology (e.g., [4] and [5]).

A quick survey of existing WBASN literature reveals that most research in this area targets problems at the physical and medium access control (MAC) layers, usually pertaining to IEEE 802.15.4 radio technology. This standard promoted by the IEEE is being widely studied and improved upon by both the industry sector and the academia. In particular, Task Group 6 targets wireless communications optimized for low power, wearable sensors that operate in, on, or around the human body [6]. Conversely, research issues pertaining to the network layer and the control plane observe modest research activity. One reason for this is that the number of sensors that can be conceivably adhered to or implanted in a human body is fairly limited. This circumstance inherently eliminates the need to implement intricate networking tasks and communications protocols as traditionally seen in computer networks. Instead, body sensors are often assumed to directly communicate with a network coordinator device (hereafter, simply referred to as coordinator) by forming a simple star network requiring limited networking functionalities.

In addition to the aforementioned, the economic drivers for using WBASN technology in both public and private sectors are evident. To date, a number of studies funded and published by diverse organizations and governments indicate that healthcare expenses are expected to rise considerably, as per the rising population of elderly people. This circumstance is aggravated by the fact that a smaller population of working-age people, whose income can be taxed to cover these expenses will soon become insufficient [7]. Consequently, it becomes of paramount importance to research WBASN technologies that may help to keep patients in relatively good/stable condition at home, which incurs a much lower cost to the healthcare provider, contrary to building more hospitals [8], [9].

A reliable and efficient health monitoring application based on WBASNs must overcome a number of hurdles before it can be safely deployed. One of many problems arise here because of radio standard homogeneity, given that we consider star-topology WBASNs formed by devices implementing the IEEE 802.15.4 specification, as previously mentioned. In order to keep hardware cost low, the WBASN coordinator would employ the same radio interface to forward relevant information digested from the collected sensor data to an access point (AP) for subsequent evaluation. However, wearable sensors are commonly assumed to employ button-cell batteries in order to improve form factor (i.e., a low-relief, overall compact device), which leads to power limitations [3]. As a result, decreased transmission power of the WBASN device has direct range implications. This circumstance combined with the severe radio signal fading effects attributed to home furniture and structural obstacles implies that

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multiple APs might be required at a single room/location in order to boost reception strength from the WBASN coordinator. Doing so ensures that a patient moving around his/her living quarters will always be within reach of a given AP. Surprisingly enough, this consideration has been overlooked in the existing literature for this subject area. Therefore, investigations into the performance of WBASN-AP handoff processes that enable uninterrupted communications are clearly warranted, as previously done in the case of WSNs [10], [11].

In addition to the aforementioned, it can be reasonably argued that a tradeoff analysis is also necessary to estimate the number of APs satisfying some minimum requirement with regards to the received signal strength (RSS), as measured by APs when a patient moves around his/her residence. (This is similar to the planning process of cellular networks in metropolitan areas.) However, it can also be argued that deploying a relatively large number of APs to cover just a single room is detrimental to the system's adoption due to cost concerns. To cope with this issue, we note that due to the intrinsic characteristics of indoors radio propagation, the RSS level measured by the AP depends on the patient's physical location and on the sensors' body placement (e.g., ankle, chest, etc.). Consequently, we are interested in studying whether using WBASN devices as temporary data relays can be effective for leveraging RSS levels at the AP, so that fewer of them are needed. We sum up the contributions of our investigations as follows.

1) We introduce a handoff protocol that can be readily implemented by WBASN coordinators and APs when the RSS of the former falls below acceptable levels. For this, we promote employing multiple radio channels in order to leverage the system's capacity, which allows monitoring multiple users in a deployment setting with several rooms.
2) We introduce a relay-search procedure that a WBASN coordinator can employ to find a sensor for temporarily forwarding vital signs data onto an AP.
3) We describe the implementation of our proposed handoff and relay search protocols, along with performance evaluations and practical experiences that take into account distinct WBASN coordinator and sensors' placement around the human body.

The remainder of this paper is organized in the following manner. Section II describes our proposed system architecture, as well as important design considerations. Section III details our handoff and relay-search protocols for WBASN handoff. In addition, we discuss the need for studying signal smoothing methods that are practicable for resource-limited, wearable sensors. Section IV describes the experiments' setup, as well as the results of our practical evaluations. Section V provides an in-depth discussion of our practical experiences and observations. Finally, Section VI concludes this paper.

II. System Architecture and Design Considerations

We now detail the foundations of our proposed system's architecture, as well as important design considerations concerning the IEEE 802.15.4 wireless communications standard. First, we generalize the applicability of the proposed health monitoring system for a deployment scenario with multiple patients, each of which wears a separate WBASN. The role of a WBASN coordinator device is to poll individual sensor devices in a predefined manner in order to collect vital signs readings before forwarding them to an AP with which is currently associated. This data can then be sent to an off-site location, where it can be scrutinized by computer algorithms and/or qualified medical personnel. Therefore, home-based health monitoring is best suited to multitier implementations [12]. Fig. 1 illustrates our proposed system architecture, which in fact adheres to the two-tiered architecture previously put forward by other researchers in the area (e.g., [13] and [14]). However, we contribute to the existing schemes by promoting a multichannel approach, whereby each WBASN worn by individual patients is assigned a different frequency channel. In addition, the channel employed by the AP to communicate with WBASN coordinators is also orthogonal to their respective operating frequencies. This enhancement effectively allows monitoring almost as many patients as available frequency channels are available to the radio transceivers. This is illustrated in Fig. 1, whereby WBASNs worn by patients located in Room 1 are each assigned an operating frequency that corresponds to the channel allocation scheme managed by the respective AP in range (e.g., $f_{\mathrm{BAN1(AP1)}}$). A benefit of the low-transmission power of wearable sensor devices is that radio channels can be reused in adjacent rooms, as long as the interference from nearby WBASNs remains negligible. For example, as shown in Fig. 1, $f_{\mathrm{BAN1(AP1)}}$ can be the same as, say, $f_{\mathrm{BAN1(AP2)}}$ if they are sufficiently separated from one another. By the same token, f_{AP2} could be the same as, say, $f_{\mathrm{BAN3(AP1)}}$. In any case, an efficient channel allocation scheme should be implemented to ensure that the health monitoring system operates reliably.

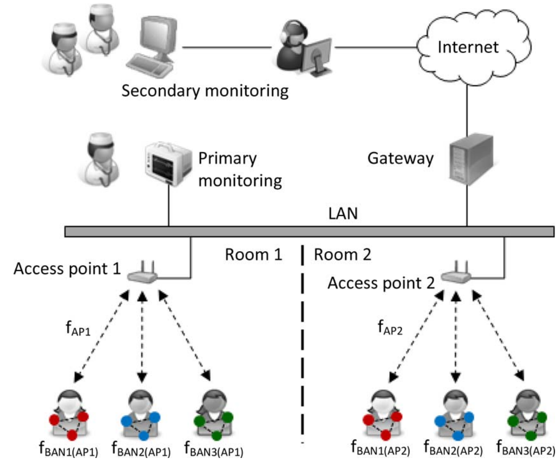

Fig. 1. Depiction of a healthcare monitoring system of convalescing patients at home based on WBASNs and multiple channel usage for improving system capacity.

The proposed multichannel system enables its deployment in places, where several patients need to be monitored at once, such as in nursing homes, or in a regular apartment. Because of the channel reuse scheme, it is possible to monitor several patient groups distributed in distinct rooms. As a result, a monitoring station should be put in place (as seen in Fig. 1), given that a typical nursing home hosts a few tens of people.

One impediment that this type of monitoring system observes is the data rate available to IEEE 802.15.4 devices, which becomes a significant limitation when in need to stream raw vital signs readings. The IEEE 802.15.4 specification stipulates a 250 kbits/s nominal data rate for point-to-point links. In practice, this value degrades significantly due to noise in the wireless channel and interference from neighbouring devices. Consider the following analysis that applies to a nonbeacon-enabled MAC scheme using this standard, where the maximum packet size for a *MAC-level protocol data unit* (*MPDU*) is set to 127 B. Here, a 13-B overhead segment is used as a minimum by the MAC layer control fields, and 114 B can be defined by the user at most. In addition, the start of frame and the frame length delimiters (SHR and PHR, respectively) add an additional 6-B overhead. Therefore, the transmission time of an MPDU amounts to: $[(127 + 5 + 1) \times 8]/(250 \times 10^3) = 4.256$ ms for a full IEEE 802.15.4 physical layer frame.

However, due to the nature of the healthcare application, it is highly desirable that the packets transmitted by WBASN devices be acknowledged. Since acknowledgement (ACK) frames span 11 B, an ACK frame transmission requires an additional 0.352 ms at a 250 Kbits/sec data rate. Yet, two additional delay values must be considered. The first is a 0.192 ms turnaround delay that the radio circuitry requires for switching from receiving mode into transmitting mode. Then, the MAC layer implementing the Carrier-Sense Multiple-Access/Collision Avoidance (CSMA/CA) channel access scheme incurs a second delay of 2.368 ms (assuming a default back-off exponent of 3). Adding all the previous values amounts to 7.168 ms. Thus, dividing the 114 B of user-defined payload by this value yields a maximum data rate of 127.2 kbits/s, which is merely one-half of the nominal data rate stipulated by this standard. On the other hand, previous research based on computer simulations suggests that more optimistic values can be achieved [15]. In either case, it is plausible that the system's capacity could degrade severely under adverse circumstances in a room, where a just handful of patients are being monitored.

Given the previous analysis, we argue that this type of health monitoring application should be targeted for use on patients in relatively stable health condition, but who still require continuous monitoring. To this end, the WBASN coordinator can then: 1) collect and preanalyze vital signs data; and 2) forward analysis results to the AP in the form of data digests (e.g., simple statistical analysis). In fact, we consider this to be a sensible mode of operation, due to the battery power limitations at the sensor nodes. Nonetheless, the system can be instructed to retrieve raw vital signs readings from individual patients on a planned schedule, and preference can be given to patients that require closer monitoring as directed by a doctor or health practitioner. Doing so ensures that scarce bandwidth is conservatively used, and that WBASN devices can preserve as much battery as possible. This approach can be implemented at the application layer, although supporting protocols at the MAC layer are pertinent [16]. Alternatively, researchers in [12] have proposed a two-radio solution to address the bandwidth scarcity problem. In this regard, the WBASN coordinator-AP link would be formed by IEEE 802.11 WLAN devices that can provide a much higher data rate. A natural counter argument is that this solution makes the system more expensive because of the extra cost incurred by the added radio interface, and because of increased battery power drain. In fact, the extra bandwidth provided by the additional WLAN radio interface is prone to being underutilized. Moreover, their design rationale considers an ECG monitoring subsystem that employs a 12-point lead. Though required for making detailed heart condition assessments at a hospital, these are not required for the type of application proposed here, where a three-point lead suffices [17]. Nonetheless, nonconventional ECG measuring schemes have also been put forward. For instance, researchers in [18] resort to indirect skin contact for long-term ECG monitoring.

Finally, because system performance depends heavily on wireless channel quality degradation, it is important for WBASN devices, and especially for the coordinator to efficiently assess link quality to the AP on a continuous basis. Using the RSS indicator (RSSI) value provided by the underlying radio interface is a good way to achieve this. As patients move around their residence, the RSSI provided by the radio module of individual sensor devices varies considerably; thus complicating the link quality assessment process. Consequently, we deem important to evaluate the performance of three distinct signal filters implemented by the sensor devices. The smoothed-out RSSI values can then be reliably referenced before making AP handoff decisions, as explained in the next section.

III. Handoff and Relay-Search Protocol Design

In this section, we describe in detail the signalling process that we have devised for: 1) a WBASN coordinator to associate and disassociate with an AP during initial power up and subsequent handoff, and 2) the search process that sensor nodes follow to designate temporary data relay with an AP. In addition, we describe the RSSI filter implementation at the APs.

A. WBASN Coordinator Association

Our proposed association protocol implements a four-way scheme for linking up with an AP that a WBASN coordinator device executes after it initially powers up, or during the second part of a handoff process. Prior to the association process start, a preliminary channel scanning action is conducted by a WBASN coordinator to discover nearby APs. In accordance to the multichannel operation scheme previously proposed, APs are assigned distinct operating frequencies depending on their actual location with the goal of minimizing cochannel interference from the APs in adjacent rooms. At power-up, a WBASN coordinator scans all 16 channels available in the spectrum band stipulated by the IEEE 802.15.4 standard. The process commences by the WBASN coordinator's issuing a PING_MSG (ping message) packet addressed to device 0, which is preassigned only to APs regardless of their locations. An AP that receives this packet type immediately acknowledges it by issuing the corresponding ACK packet type. In fact, all system devices are preprogrammed to automatically issue an ACK packet immediately after receiving a packet of any type. Upon receiving the ACK packet, the coordinator queries its radio interface to

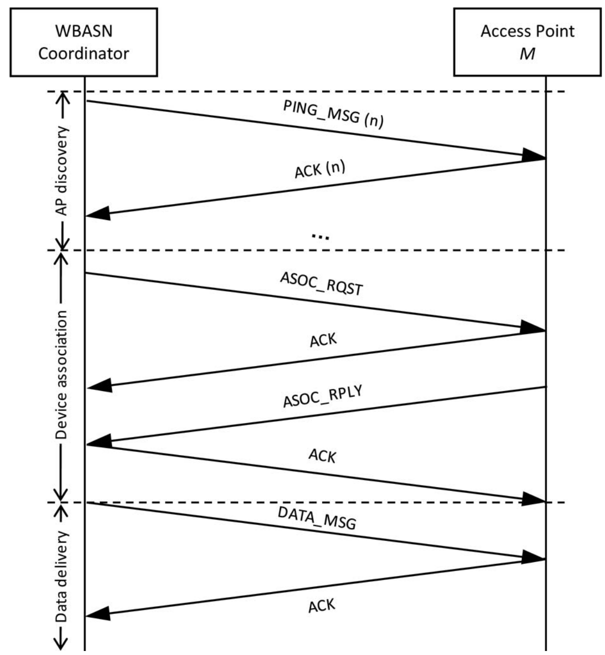

Fig. 2. Signalling protocol for the (re)association and handoff process between a WBASN coordinator and AP *M*.

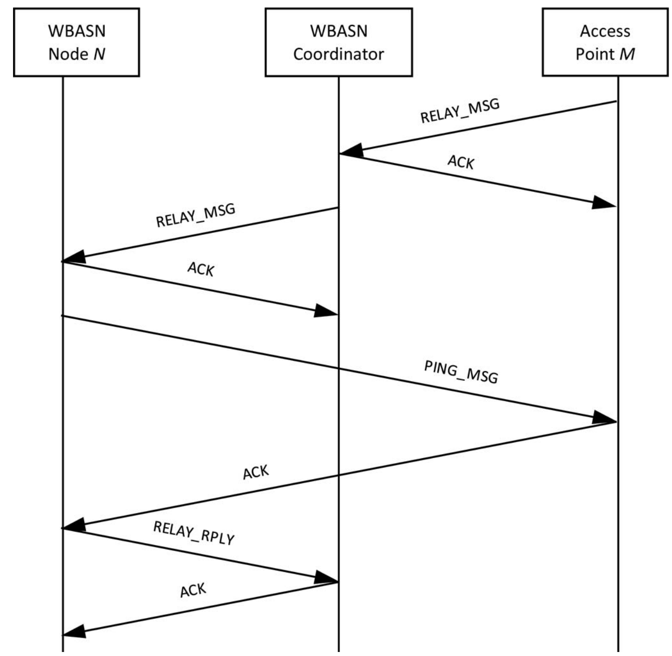

Fig. 3. Signalling protocol for the relay-search process between an AP *M*, and the WBASN coordinator and sensors.

retrieve the instantaneous RSSI value associated with the ACK packet just received, and the ID of the issuing AP. This value pair is temporarily stored before tuning the radio into the next channel to perform the same AP discovery process. Failure to receive an ACK from an AP triggers a timeout event that automatically resumes the channel scanning process. An ACK packet that yields a higher instantaneous RSSI value replaces the preceding one, so that only the best outcome is maintained.

Once the preliminary discovery stage completes, the WBASN coordinator initiates the association process with the AP that registered the highest instantaneous RSSI value. The process begins by having the coordinator retune its radio into the channel being used by the chosen AP, and then, issuing an ASOC_RQST (association request) packet. The AP automatically responds with the corresponding ACK signal, which is shortly followed by an ASOC_RPLY (association reply) packet. This response packet contains the necessary parameters that the WBASN coordinator needs to know in order to commence operations (e.g., the intra WBASN channel, data collection rate, vital signs to monitor, etc.). We note that ASOC_RPLY packets are issued independently from ACK packets because the corresponding IEEE specification does not make any provisions for the latter type to include user-defined information, as needed by our customized application. Finally, the WBASN coordinator enters the CONNECTED state as soon as the ACK reply for the corresponding ASOC_RPLY packet is received. The coordinator then issues periodic DATA_MSG (data message) packets to the AP in order to keep the central monitoring station informed of the patient's most current health status. We also note that APs individually maintain a registry of the WBASN coordinator devices being supervised. This registry includes a state variable describing the current association stage of WBASNs, which is updated in an ongoing basis. Fig. 2 illustrates the corresponding signalling process of this WBASN coordinator-AP association protocol. At this point, APs monitor all WBASN coordinator transmissions to gauge their corresponding RSSI level.

B. Relay Assessment Process

As mentioned earlier, RSSI levels decaying below a preliminary "soft" threshold will inevitably be observed as the patient moves around his/her residence. When this happens, the AP indicates the relay-search procedure commencement in an attempt to leverage the received radio signal level. If the process' outcome is successful, then the coordinator forwards DATA_MSG packets through the designated WBASN node that currently yields a better RSSI level because of its current physical orientation to the AP, and its placement on the patient's body. Fig. 3 illustrates the signalling protocol for the relay-search process, which we detail next.

The AP triggers the relay-search process by issuing a RELAY_MSG (relay message) packet to the WBASN coordinator, whose RSSI signal has decayed below a "soft" threshold. We note that WBASN devices might be in a low-power, sleep-mode at the moment that the packet is received by the coordinator, and so the process might experience some delay until the sensor's radios are switched back ON. When this happens, the WBASN coordinator simply broadcasts the RELAY_MSG packet to the WBASN nodes, which in turn follow by individually sending a PING_MSG packet to the AP. The latter then automatically replies an ACK packet to each sensor to obtain an instantaneous RSSI measurement. After this, each sensor sends a RELAY_RPLY (relay replay) packet containing the respective RSSI value to the WBASN coordinator. As mentioned earlier, the WBASN coordinator simply stores the identity of the sensor that yields the highest RSSI reading above the soft threshold, if any. The coordinator then forwards subsequent DATA_MSG packets to the corresponding sensor node selected as data relay, and the rest of the sensors resume regular operations.

This operation mode continues insofar as the selected relay node's transmissions yield an acceptable RSSI reading at the AP. Evidently, the relay node's duty cycle changes in order to accommodate WBASN-AP communications. This process is performed again if the patient's motion causes the RSSI values of the corresponding WBASN to decay below the soft threshold. This provision enables a "fall-back" mechanism that resumes point-to-point communications between the WBASN coordinator and the AP. At this point, no WBASN device will continue to relay data as long as the coordinator's own transmissions yield an acceptable RSSI reading. It also follows that the process can be repeated as necessary, until either the WBASN coordinator or any other sensor no longer provides a RSSI level above the hard threshold. At this time, the only solution is to initiate the handoff procedure that disassociates the WBASN coordinator from the current AP, and reassociate with a new one.

C. WBASN Handoff

As seen in Fig. 4, the AP issues a HNDF_CMD (handoff command) packet to the WBASN coordinator in order to begin the handoff process if the hard threshold is crossed. At this point, the WBASN coordinator replicates the initial AP association procedure until a new AP with a better signal strength is found. Upon associating with a new AP, the WBASN coordinator momentarily returns to its prior operating frequency to issue a FOLLOW_ME command. In doing so, sensor devices are instructed to retune their radios to the channel of the new AP that the coordinator just associated to. Finally, the WBASN coordinator also retunes its radio to this new channel in order to resume normal operation. For simplicity, we refer to the sensors' retuning process as "sensor herding." From this explanation, it follows that WBASN devices also associate with their coordinator immediately after power-up. Therefore, unless herded into a new operating frequency, WBASN devices will operate in the same channel. In the end, the AP always decides the operating frequencies of all associated WBASNs in range, so that no overlaps occur.

D. RSSI Estimation at the AP

IEEE 802.15.4 radio devices are highly susceptible to fast-fading effects of the wireless channel they operate on [19]. Since this radio standard is widely favoured for WBASN implementations, its propagation characteristics as affected by the human body are being explored at present [20], [21]. With regards to our investigations, the operation and performance of the handoff and relay-search protocols that we propose can be notably influenced by wide variations in RSSI values measured as well. This circumstance warrants the implementation and use of signal filtering techniques in order to obtain a smoother RSSI value sequence that can be reliably referenced [22]. Consequently, we examine the performance of popular signal filtering algorithms that are practicable in resource-constrained sensor devices, and disregard other popular and effective filtering techniques that impose a prohibitively high algorithmic cost, such as particle filtering.

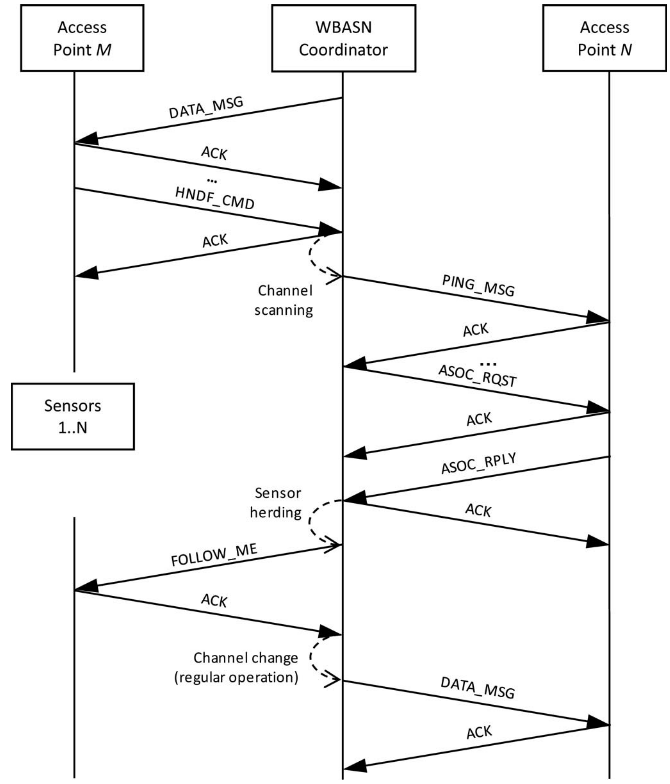

Fig. 4. Signalling protocol for the (re)association and handoff process between a WBASN coordinator and APs, including sensors' retuning their radios into a new channel.

1) Simple Moving Average: This is the most basic signal filtering method that we consider, in which a sequence of RSSI values is summed over and divided by the total number of k samples in order to get a simple averaged value

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

The subscript t accompanying RSSI values v in (1) indicates time dependence. This implies that the oldest measurement is discarded and replaced by the most recent one in a window-shifting fashion. Smaller values for k yield a more irregular filter output that is vulnerable to large RSSI magnitude variations. On the contrary, larger values for k value make the filter more immune to such type of variations, though it introduces an undesirable output lag.

2) Discrete Kalman: The Kalman filter is a popular filter that is amply employed in signal processing applications, as it is able to produce a high-fidelity output. In fact, its performance in support of device handoff for IEEE 802.11 networks has been recently evaluated [23]. The Kalman filter can be represented in the following form:

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

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

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

$$\hat{x}_k = \hat{x}_k^- + K_k \times (z_k + H\hat{x}_k^-) \tag{5}$$

$$P_k = P_k^- \times (I - K_k H). \tag{6}$$

Expressions (2) and (3) of this family of equations are employed for time update, whereas expressions (4)–(6) are used for measurement update. To compute the output, the algorithm iterates through each RSSI packet measurement. To this end, **A** and **B** represent a $n \times n$ state transition matrix, and a $1 \times n$ control input matrix, respectively, for a state x, whereas **H** represents the $m \times n$ matrix ascribed to the current measurement state. In addition, **Q** represents the process matrix, and **R** represents the measurement noise covariance matrix. Finally, the term K represents the Kalman gain, P is the covariance estimate, $\hat{x}$ is the state estimate, and u is the control input value. Depending on the application, the Kalman filtering technique may place a considerable computational burden for a microcontroller unit (MCU) at the heart of a sensor node. However, the preceding family of equations can be significantly simplified by assuming a stationary RSSI value that is observed in the case of patients, who remain mostly static. In this case, the value of matrices **A** and **H** are both set to 1, whereas **B** is set to 0, since there is no control signal in our system, and subscript k is dropped.

3) Exponential Smoothing: The third filtering technique that we consider is algorithmically simpler than the Kalman filter and produces an output of weighted averages for all future computations, as illustrated in the following equation:

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

The most important simplifying feature of this filtering technique, as compared to the Kalman filter, is that the value of the gain weight α is fixed, making it computationally less intensive for a resource-constrained MCU. As seen in the previous techniques, the weigh value used here determines the autocorrelation degree, which ultimately controls the effect that large input values have on the computed output, in addition to the lag effect mentioned earlier.

IV. Evaluation Setup, Results, and Discussion

A. Experiment Setup

In this section, we describe the practical evaluation setup of our proposed system. Even though previous research has reported practical WBASN implementations (e.g., [24]), no performance reports of handoff protocols in combination with sensor placement effects and data relaying have been reported. We programmed our proposed scheme in the NesC language for deeply embedded sensor networks to produce a TinyOS (version 2.1) [25] binary image that can be loaded into TelosB sensor nodes [26]. In addition, we employed 2 APs: one based on a MIB600 board, and a second based on a MIB510 board, both employing Micaz hardware as their radio gateway [26]. We strapped four sensors to our test subject, as illustrated in Fig. 5: one on the upper left-arm/shoulder area, one on the left wrist, one on the right-hand side of the waist/hip area, and the last one on the right-hand side ankle. The waist/hip area sensor was placed facing to the front of the subject's body, and the other three facing outward.

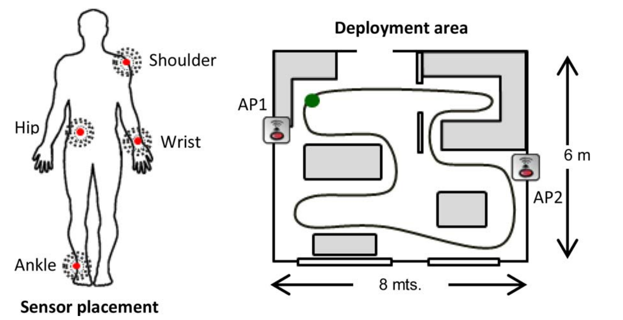

Fig. 5. Illustration of: 1) the WBASN devices' placement on a test subject for our experiments; 2) the trajectory followed by the subject during tests; 3) the deployment area with shadowed obstacles; and 4) the location of the AP. The dot indicates the starting and turn-around point.

The reason for securing WBASN devices in these body areas is explained as follows. Given that the shoulder area has the advantage of being located high in the human body when in standing posture, it becomes a natural location choice for attempting line-of-sight communications with APs. In addition, ECG sensors are often located in the upper chest, which is very close to the shoulder. Placing a WBASN sensor over the wrist area is a plausible choice too, given that some commercially available wristwatches already possess some biometric functionality (lacking only a low-power transmitter). In fact, prototype WBASN nodes inside timepieces already exist [27]. The hip/waist area results highly attractive for placing a WBASN coordinator using popular-size AA or AAA batteries, contrary to the button-cell type otherwise favoured for regular WBASN devices as per their form factor. Finally, the ankle area is a plausible one to strap a WBASN sensor employed for posture and fall detection, as recently proposed by researchers [28], [29].

With regards to the deployment setting, we decided to run our tests in an actual apartment (contrary to a conventional computer laboratory), in order to gauge its performance in a place, where we would expect to see a patient recovering from, say, an operation, or noncritical illness. The right-hand side of Fig. 5 displays a rough sketch of our deployment setting, including the trajectory that our test subject followed at 0.5 m/s, and 1.0 m/s for different experiments. We regard these walking paces as realistic for recovering patients at home. Each experiment involved an interleaved walking cycle of the deployment setting that totalled 20 rounds: 10 times in one direction, and 10 times in the opposite direction. Otherwise, by performing walking cycles in a single direction, WBASN devices observe the multipath fading effects from one movement perspective, but not from the one observed by walking in the opposite direction. Therefore, the interleaved rotation in the walking cycle eliminates bias in the results. In addition to this, the role of the WBASN coordinator was cycled among the four sensors in order to measure the number of lost packets, as well as sensor utilization when assuming the data relay role. When walking at 0.5 m/s, the cycle lasts around 1 min, and at 1.0 m/s, around half minute. We enforced the walking pace in each experiment as rigorously as possible, though ±2-s fluctuations were regularly observed. All

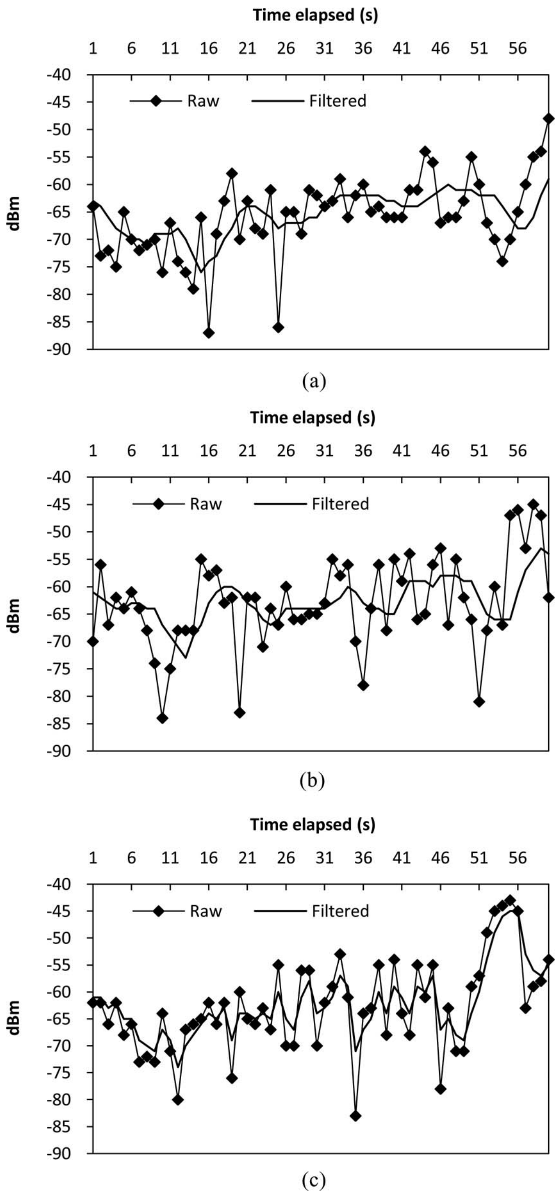

Fig. 6. Performance of RSSI filters implemented at the APs. (a) Moving average with ten sampled values. (b) Discrete Kalman ($Q = 0.5$ and $R = 5$). (c) Exponential smoothing ($\alpha = 0.5$). Subject's speed is 0.5 m/s.

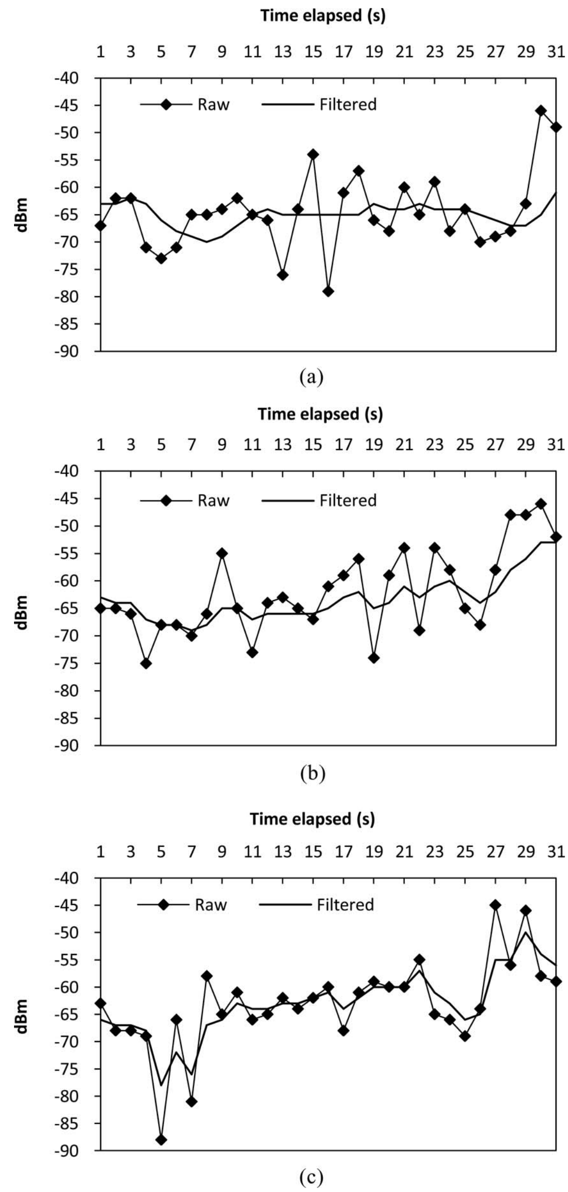

Fig. 7. Performance of RSSI filters implemented at the APs. (a) Moving average with ten sampled values. (b) Discrete Kalman ($Q = 0.5$ and $R = 5$). (c) Exponential smoothing ($\alpha = 0.5$). Subject's speed is 1.0 m/s.

WBASN devices employed their full 0 dBm (1 mW) transmission power, and the coordinator was set to communicate with the corresponding AP once every second. For simplicity, APs were designated to collect both sensor utilization and lost packets measurements, which in turn were forwarded to a PC for subsequent processing.

B. Tests Results

Figs. 6 and 7 illustrate sample plots of RSSI readings made for each of the two walking speeds considered: 0.5 and 1 m/s, respectively. We obtained these data using only AP1 placed, as shown in Fig. 5, and the lone WBASN coordinator placed at the waist/hip of the tests' subject in order to gauge the performance of the three types of filters implemented. Raw RSSI values are evidently similar because they were measured along the exact same walking cycle. Figs. 6(a) and 7(a) depict sample plots obtained by the simple moving average algorithm described in (1), which employs 10 RSSI readings in a moving window fashion to compute its output. After continuous experimentation, we found that this number satisfactorily reduces the changes in magnitude of the RSSI readings without experiencing excessive lag, although this choice is subject to the surrounding environment of our deployment setting. Because of the slow walking pace at 0.5 m/s, AP1 samples RSSI values at a higher resolution, thus observing magnitude variations of up to ± 20 dBm for consecutive readings, which reveals the presence of a fast-fading channel. On the other hand, a lower RSSI value sampling rate at 1.0 m/s does not produce the wide variations from one reading into the next.

Figs. 6(b) and 7(b) depict the corresponding plots for the (simplified) discrete Kalman algorithm that we implemented and described through (2)–(6), in which we employed the parameters $Q = 0.5$ and $R = 5$. On the one hand, a simple visual inspection of Fig. 6(b) does not evidence a clear superiority of this algorithm over the Simple Moving Average. However, for the 1.0 m/s case, the Discrete Kalman filtering technique displays a better response to larger RSSI readings' variations. At the same time, the filter's output is less affected by previous variations without the unwanted lag effects. Nonetheless, the effectiveness of this filtering algorithm is not fully realized, as per the simplifications that were introduced for the case of the state transition matrices **A** and **H**. The alternative is to formulate the corresponding transition probability matrices for each case. This requires a good radio propagation model at hand that is applicable to home environments. At present, this is a matter of intense research [3].

Figs. 6(c) and 7(c) illustrate the behaviour of the exponential smoothing filtering algorithm for with $\alpha = 0.5$, which causes the filter to show minimal response to small variations of RSSI measurements. Consequently, the obtained output displays negligible lag, while still discriminating large variations. Additional experimentation using a much smaller value for α (e.g., 0.1) produced a filtered output nearly identical to the discrete Kalman filter. However, the exponential smoothing algorithm is computationally more efficient. To this regard, algorithmic efficiency is crucial because floating point operations as required by the filtering algorithms are implemented through software routines in the MCU of the TelosB sensor nodes. This circumstance leads to increased memory use, execution times, and power consumption. Therefore, we ultimately decided to employ this filtering algorithm for our subsequent experiments.

Because we wanted to have our system enter the relay-search process relatively often, we decided to set up the "soft" decision threshold at –60 dBm. After repeated pilot runs, we observed that the lost packet count noticeably increased as the filtered RSSI output approached this value. We had also observed that as the test subject crossed the boundary between adjacent rooms inside the deployment setting, the filtered RSSI output lingered around –70 dBm and the lost packet count increased markedly. Therefore, we set up this to be the handoff decision threshold. Fig. 8(a) and (b) illustrates our system's performance in terms of lost packets. This parameter was measured by the two APs in operation while carrying out the respective walking cycle with the WBASN in place, as previously explained. For all, but the coordinator-at-the-hip case, using sensors as temporary data relays yielded fewer lost packets when the test subject walked at 0.5 m/s. Evidently, sensor placement had a positive effect on the overall system performance. To this regard, the packet loss count decreased at a twofold rate for the coordinator-at-the-shoulder case, a fivefold rate for the coordinator-at-the-wrist case, and more than a threefold rate for the coordinator-at-the-ankle case (no decrease observed for the coordinator-at-the-hip case). These results corroborate our previous assumptions, being that radio transmissions at the ankle level (i.e., near the ground) were unequivocally susceptible to signal distortion. Nonetheless, we also observe that at 1.0 m/s, the relayed data scheme provided no benefits when compared to solely using the WBASN coordinator for data transmission.

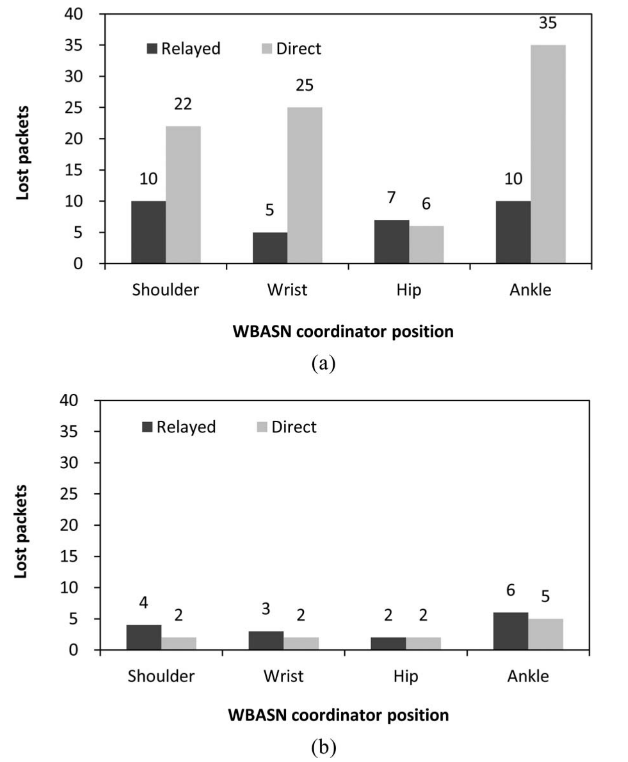

Fig. 8. Lost packet performance at: (a) 0.5 m/s, and (b) 1.0 m/s using relayed and direct (nonrelayed) WBASN transmissions. The exponential smoothing filtering technique was used to estimate RSSI values.

Fig. 9 depicts individual sensor device utilization as data-forwarding relays with respect to their body placement. The results depicted therein correspond to measurements taken for each individual sensor, while the whole of them were operating simultaneously. There, plots (a)–(d) illustrate results for the 0.5 m/s walking pace, whereas plots (e)–(h) do so for the 1.0 m/s case. For instance, in the coordinator-at-the-shoulder case, this device is utilized 61% of the experiment's run time at a walking speed of 0.5 m/s, whereas the wrist, hip, and ankle sensors observe a 28%, 6%, and 5% of individual utilization as data relays, respectively. As mentioned earlier, these are the combined results reported by both APs. The outcome for both walking paces show that the wrist sensor is utilized the most as data relay. Conversely, the ankle sensor always observes the lowest utilization among them all. Another observation is that the combined sensors' utilization as data relays fluctuates between 31% and 40% for most cases, except for those shown in plots (d) and (g), where this utilization increases to 44% and 46%, respectively. In other words, the combined sensors' utilization as data relays is significant.

C. Discussion

We further discuss important aspects observed in our results. We initially anticipated a higher relay utilization rate for the shoulder sensor because of its higher likelihood to observe a direct line-of-sight with the APs. To our surprise, the wrist

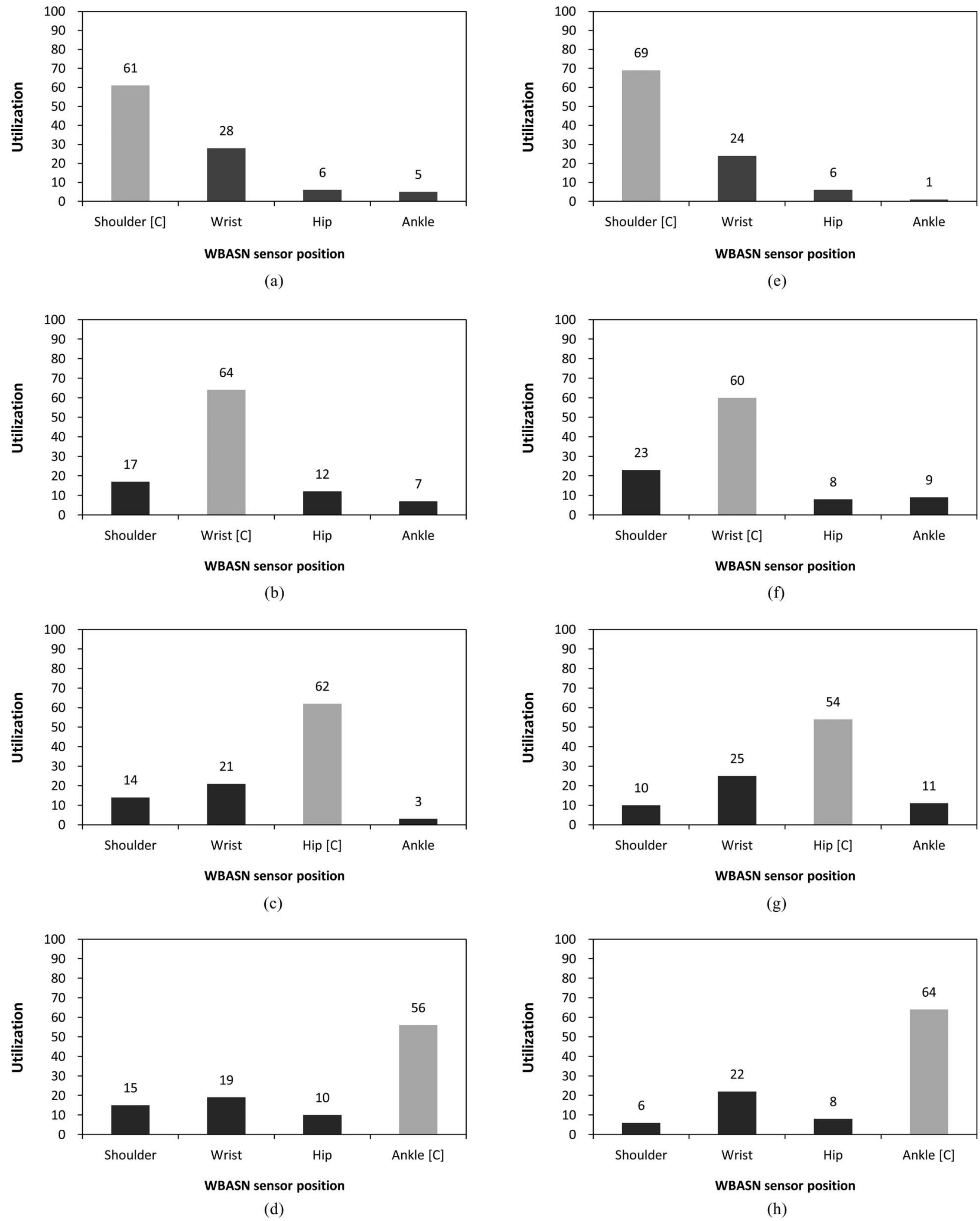

Fig. 9. Relay utilization for patients walking at 0.5 m/s as depicted in (a)–(d), and at 1.0 m/s as depicted in (e)–(h) for each respective sensor and the corresponding coordinator position [C].

sensor observed the highest utilization rate as a temporary relay after the WBASN coordinator. Neither the coordinator's placement, nor the subject's walking pace, or even the arm's (natural) angular swinging motion influenced this outcome. Another surprising result, as illustrated in Fig. 9, was that when the WBASN coordinator was placed at the ankle, it observed a higher utilization rate compared to the coordinator-at-the-hip, and the coordinator-at-the-wrist cases for a 1.0 m/s walking pace.

Finally, we elaborate on practical aspects of our proposed system. First, assigning the WBASN coordinator role to a sensor node placed inside a wristwatch appears to be a reasonable option, as suggested by our results. However, the downside of this would be that the button-cell battery regularly employed to power this device type would certainly drain much quicker. Therefore, new research efforts aimed at energy harvesting schemes becomes a sensible course of action to leverage the effectiveness of battery power sources [30], [31]. Another practical consideration is using accelerometers to estimate the walking pace of a patient. In doing so, the relay-search system can be enabled if the corresponding algorithm determines that the patient is walking slowly. As illustrated by our findings, this is when using regular sensors as temporary relays results more efficient. Conversely, the relay-search process could be disabled when a patient walks faster, given that using the data relaying scheme yields no measurable benefits at 1.0 m/s. Similarly, long-term experimentations of the benefits introduced by relaying data through sensors at different walking paces are warranted.

We also note that all of our experiments involve a patient in constant motion. Nonetheless, additional pilot experiments showed that a WBASN coordinator's RSSI measurements may degrade considerably when a patient is static at a location that hinders radio propagation. Hence, the data relaying scheme may result beneficial in this case, though it might not occur using body sensor devices, but off-WBASN nodes instead located in items near the patient (e.g., a reading lamp, a telephone, a music player, etc.). This observation reveals that although the proposed system might soon become available for home-based use, its installation would require a skilled wireless network deployment. In addition, the proposed system would greatly benefit from hardware implementing antenna diversity techniques to mitigate the effects of multipath fading. In the end, employing fewer APs would readily translate into a more economical system deployment, while still being able to perform efficiently. Wireless network coexistence techniques are also warranted, given the nature of the application.

V. Conclusion

We presented a handoff and data relaying scheme that facilitates healthcare monitoring for mobile patients at home. Our results show WBASN devices used as temporary data relays may help to decrease the lost packet rate when patients walk at 0.5 m/s. We observed that the placement of the WBASN coordinator in the patient's body directly influences the overall performance of our proposed system. To this regard, the wrist position provided the best results for designating as a temporary data relay, regardless of where the WBASN coordinator is located. On the other hand, though naturally favoured by an AP line-of-sight, the shoulder position may not yield the best radio signal strength. We are confident that our findings will motivate further research in this area, including energy harvesting schemes that help to offset the lifetime of batteries employed to power sensor devices.

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