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# Technical Report

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## Abstract

Handoff processes, the events where mobile nodes select the best access point  vailable to transfer data, have been well studied in cellular and WiFi networks. However, wireless sensor networks (WSN) pose a new set of challenges due to their simple low-power radio transceivers and constrained resources. This paper proposes smart-HOP, a handoff mechanism tailored for mobile WSN applications. This work provides two important contributions. First, it demonstrates the intrinsic relationship between handoffs and the transitional region. The evaluation shows that handoffs perform the best when operating in the transitional region, as opposed to operating in the more reliable connected region. Second, the results reveal that a proper fine tuning of the parameters,in the transitional region, can reduce handoff delays by two orders ofmagnitude, from seconds to tens of milliseconds.

# smart-HOP: a reliable handoff mechanism for mobile wireless sensor networks*

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**Abstract.** Handoff processes, the events where mobile nodes select the best access point available to transfer data, have been well studied in cellular and WiFi networks. However, wireless sensor networks (WSN) pose a new set of challenges due to their simple low-power radio transceivers and constrained resources. This paper proposes smart-HOP, a handoff mechanism tailored for mobile WSN applications. This work provides two important contributions. First, it demonstrates the intrinsic relationship between handoffs and the transitional region. The evaluation shows that handoffs perform the best when operating in the transitional region, as opposed to operating in the more reliable connected region. Second, the results reveal that a proper fine tuning of the parameters, in the transitional region, can reduce handoff delays by two orders of magnitude, from seconds to tens of milliseconds.

## 1 Introduction

Mobility management represents a major requirement in several emerging ubiquitous and pervasive sensor network applications, including health-care monitoring, intelligent transportation systems and industrial automation [1–3]. In some of these scenarios, mobile nodes are required to transmit data to a fixed-node infrastructure in real-time. For example, in clinical monitoring [4], patients have embedded wireless sensing devices that report data through a fixed wireless network infrastructure. In this type of scenarios, it is necessary to provide a reliable and constant stream of information.

A naive solution in these applications is for sensor nodes to broadcast the information to all access points (APs) within range. This approach, while simple, has a major limitation. Broadcasts lead to redundant information at neighboring APs (since several of them receive the same packets). This implies that the fixed infrastructure will have to either waste resources in forwarding the same informationto the end point, or it will need complex schemes, such as data fusion, to eliminate duplicated packets locally.

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A more efficient solution is for mobile nodes to use a single AP to transmit data at any given time. This alternative would require nodes to perform reliable and fast handoffs between neighboring APs. Handoffs have been studied extensively in other wireless systems [5–12], in particular cellular and WLAN networks. However, these techniques are not suitable for WSN due to their unique characteristics. Contrary to more complex systems, such as cellular networks, which have advanced spread spectrum radios and almost unlimited energy resources, WSN have severely constrained resources. Furthermore, low-power links have shorter coverages and higher variability, which requires a more careful evaluation of the handoff parameters.

Our study addresses the design, implementation and evaluation of smart-HOP, a handoff mechanism tailored for mobile WSN applications. We perform a systematic analysis of the different parameters involved in the handoffs of mobile nodes in WSN. Our evaluations reveal that a proper fine tuning of the parameters can reduce the handoff delay from seconds to tens of milliseconds. The results also show that the best handoff performance is in a transitional region (a region that contains unreliable links).

The remainder of the paper is organized as follows. In Section 2, we describe the problem at stake and the main reasons to design a new handoff method for mobile WSNs. In Section 3, we describe the smart-HOP mechanism and its most important parameters. The evaluation set-up and the analysis of the parameters is presented in Section 4. The impact of radio interference is discussed in Section 5. Section 6 addresses the related work in the area, and Section 7 provides our conclusions and a discussion of future work.

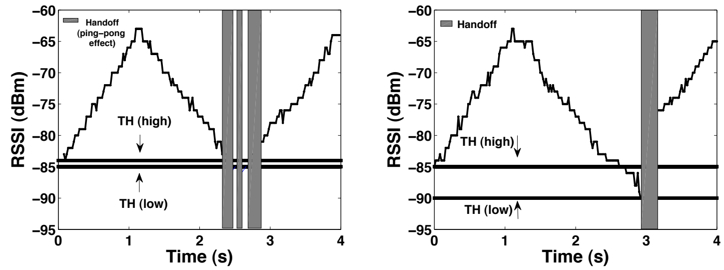
## 2 Problem statement

This section describes the need to calibrate handoffs according to the particular characteristics of mobile WSNs and the parameters that should be taken into account when designing a handoff mechanism.

### 2.1 Considering WSNs limitations

In a nutshell, a handoff mechanism should answer two questions: when should the handoff start? and when should it end? We define handoff in WSN as the process where a mobile node changes the destination address of its data packets from one access point to another. In practice, a handoff starts when the link with the current (serving) AP drops below a given value ($TH_{low}$) and stops when it finds a new AP with the required link quality ($TH_{high}$). A detailed overview of the handoff mechanism is presented in Section 3.

Figure 1 depicts the importance of performing a thorough evaluation of the parameters. The y-axis shows the RSSI detected by the serving AP and the vertical bars denote the handoffs performed. Central to this evaluation is to consider the unique characteristics of low-power links. The transitional region in sensor networks, for the CC2420 radio transceiver, encompasses the approximate range [-90 dBm, -80 dBm] (shown in Figure 4). Intuition may dictate that the closer the handoff is performed to the connected region the better (because links are more reliable). Figure 1(a) depicts this conservative approach. It considers




(a) (b)

**Fig. 1.** (a) an example of an inefficient handoff, (b) an example of an efficient handoff

-85 dBm as the lower threshold, and the upper threshold is 1 dB higher. These parameters lead to a negative effect: a long delay (≈0.7 s) that takes three handoffs between the two contiguous APs (ping-pong effect). Figure 1(b) shows that by considering a wider margin, deeper into the transitional region, the ping-pong effect disappears and the delay is reduced to approximately 0.2 s. In Section 4, we will observe that a careful calibration of the parameters can reduce the handoff delay to the order of tens of milliseconds.

### 2.2 Design considerations

We now present the most important issues that should be considered when designing a handoff mechanism for WSN.

**Hard handoffs.** The type of handoff is dictated by the capabilities of the radio. Handoffs are classified into two main categories: hard handoffs and soft handoffs. In a *soft handoff*, the radio can use multiple channels at the same time. This characteristic enables a mobile node to communicate with several APs and assess their link qualities while transmitting data to the serving AP. A common technology used in soft handoffs radios is code division multiple access (CDMA) [13]. In a *hard handoff*, the radio can use only one channel at any given time, and hence, it needs to stop the data transmission before the handoff process starts. Consequently, in hard handoffs it is central to minimize the time spent looking for a new AP. WSN nodes typically rely on low-power radio transceivers that can operate on a single channel at a time, such as the widely used CC2420. This implies that current WSN should utilize a hard handoff approach.

**Low-power and unreliable links.** Low power links have two characteristics that affect the handoff process: short coverage and high variability [14]. Short coverages imply low densities of access points. In cellular networks, for example, it is common to be within the range of tens of APs. This permits the node to be conservative with thresholds and to select links with very high reliability. On the other hand, sensor networks may not be deployed in such high densities, and hence, the handoff should relax its link quality requirements. In practice, this implies that the handoff parameters should be more carefully calibrated within the (unreliable) transitional region.

The high variability of links has an impact in stability. When not designed properly, handoff mechanisms may degrade the network performance due to the ping-pong effect, which consists in mobile nodes having consecutive and redundant handoffs between two APs due to sudden fluctuation of their link qualities. This happens usually when a mobile node moves in the frontiers of two APs. Hence, to be stable, a handoff mechanism should calibrate the appropriate thresholds according to the particular variance of its wireless links.

## 3 The smart-HOP mechanism

Conceptually, a wireless handoff is a simple process, but in order to make it efficient, several parameters need to be analyzed thoroughly. In this section, we provide the overall idea of smart-HOP and highlight the importance of three parameters: link monitoring, hysteresis thresholds and stability monitoring. In the next sections, we evaluate the impact of these parameters in the performance of three important metrics: delivery rate, handoff delay and handoff stability.

The smart-HOP algorithm has two main phases: *(i) data transmission* and *(ii) discovery*. A timeline of the algorithm is depicted in Figure 2.

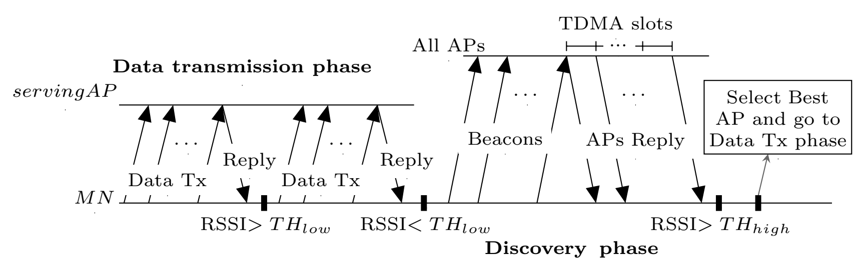



**Fig. 2.** Time diagram of the smart-HOP mechanism

For the sake of clarity let us assume that a node starts in the Data Transmission Phase[4]. In this phase, the mobile node has a reliable link with an AP, defined as serving AP in Figure 2. The mobile node monitors the link quality by receiving *reply* packets from the serving AP. Upon receiving $n$ data packets in a given window $w$, the serving AP replies with the average received signal strength (RSSI), or signal-to noise ratio (SNR), of the $n$ packets. If no packets are received, the AP takes no action. This may lead to disconnections, which are solved through the use of a time-out mechanism (explained later). The differences between the RSSI and SNR metrics are explained in Section 5 when smart-HOP is evaluated under the presence of interference. It is important to notice that smart-HOP filters out asymmetric links implicitly by using reply packets at the data transmission and discovery phases. If a neighboring AP does not have active links in both directions, the node is simply not part of the process. The three main prameters used for tuning smart-HOP are explained extensively as follows:

[4] smart-HOP has a simple initialization phase that is similar to the discovery phase.

*Parameter 1: link monitoring.* The first important parameter in a handoff process is to determine how frequent the link monitoring should be. The link monitoring property is captured by the Window Size ($WS$) parameter which represents the number of packets required to estimate the link quality. A small $WS$ (high sampling frequency) provides detailed information about the link but increases the processing of reply packets, which leads to higher energy consumption and lower delivery rates. On the other hand, a large $WS$ (low sampling frequency) provides only coarse grained information about the link and decreases the responsiveness of the system. Some studies on link quality estimation have reported that three continuous packets provide accurate link-quality status for high sampling rates [15] – which is the type of scenarios we evaluate. We performed experiments that validated these results, and hence, we utilize $WS = 3$. Considering that we use an inter-packet time of 10 ms, $WS = 3$ maps to a sampling rate of 33 Hz.

The mobile node starts the Discovery Phase when the link quality goes below a certain threshold ($TH_{low}$) and looks for APs that are above a reliable threshold ($TH_{high} = TH_{low} + HM$, where $HM$ is the hysteresis margin). During the discovery phase, the mobile node sends three continuous beacons, and the neighboring APs reply with the average RSSI or SNR of the beacons. In order to reduce the effects of collisions, the APs use a simple TDMA MAC, which is described later in Section 4. If one or more APs are above $TH_{high}$, the mobile node connects to the AP with the highest quality and resumes data communication, else, it continues broadcasting 3-beacons bursts until discovering a suitable AP. The reasoning behind using three beacons is the same as for link monitoring, i.e., a good trade-off between accuracy and responsiveness.

*Parameter 2: handoff thresholds and hysteresis margin.* In WSNs, the selection of thresholds and hysteresis margins is dictated by the characteristics of the transitional region and the variability of the wireless link. The lowest threshold has to consider the boundaries of the transitional region. If the threshold is too high, the node could perform unnecessary handoffs (by being too selective). If the threshold is too low the node may use unreliable links. The hysteresis margin plays a central role in coping with the high variability of low-power wireless links. If the margin is too narrow, the mobile node may end up performing unnecessary and frequent handoffs between two APs (ping-pong effect). If the margin is too wide, the handoff may take too long which ends up increasing the delay and decreasing the delivery rate. A thorough evaluation of these parameters is presented in the next section.

*Parameter 3: stability monitoring.* Due to the high variability of wireless links, the mobile node may detect an AP that is momentarily above $TH_{high}$, but the link quality may decrease shortly after being selected. In order to avoid this, it is important to assess the stability of the AP candidate. After detecting an AP above $TH_{high}$, smart-HOP sends $m$ further 3-burst beacons to validate the stability of that AP. Stability monitoring is tightly coupled to the hysteresis margin. A wide hysteresis margin requires a lower $m$, and vice versa. In the next section, we will observe that an appropriate tuning of the hysteresis margin can lead to $m = 1$.

*Architectural design.* smart-HOP has some distinct design features. Most handoff methods perform explicit disconnections, i.e., the node informs the old AP that it no longer needs it. smart-HOP does not perform these disconnections for two reasons. First, sensor network deployments may have a limited overlap between neighboring APs – due to low coverage radios and low node density–, and this limited overlap may not permit complex transactions (by the time a mobile node wants to disconnect, the AP may already be out of range). Second, removing explicit disconnections reduces the computational and transmission costs of mobile nodes. Applications similar to cellular networks perform explicit disconnections because they provide circuit switching services (dedicated communication channel). We argue that for several applications envisioned in mobile sensor networks (reliable transfer of information from mobile nodes to a fixed infrastructure), handoffs do not require explicit disconnections.

The lack of explicit disconnections implies that the fixed infrastructure is not responsible to track the connectivity of mobile nodes (as opposed to what happens in cellular networks). Hence, the mobile node should take an active role in avoiding disconnections. This is simply done by maintaining a disconnection time-out. If the mobile node does not receive *reply* packets for a certain period of time, it starts the discovery phase. The time-out parameter depends on the real-time requirements of the application, in our case it was set to 100 ms.

## 4 Parameter Calibration

### 4.1 Test-bed setup

Calibrating the parameters of smart-HOP requires a testbed that provides a significant degree of repeatability. A fair comparison of different parameters is only possible if all of them observe similar channel conditions. In order to achieve this, we deploy a model-train in a large room. The room is 7 m×7 m and the locomotive follows a 3.5 m×3.5 m square layout. The speed of the locomotive was approximately 1 m/s (average walking speed). Figure 3(a) depicts a locomotive passing by an AP and Figure 3(b) shows the experimental scenario.

In real-world applications, the deployment of access points (or base stations) is subject to an accurate study to ensure the coverage of the area of interest. In cellular networks, the density of access points guarantees full coverage and redundancy. In other wireless networks, the density of access points depends on the real-time requirements of the application. In critical applications, such as the one considered in our paper, complete coverage is an essential requirement. To prevent extreme deployment conditions such as very high or very low density of APs, our tests provide minimal overlap between contiguous APs. However, the distribution of access points is out of the scope of our paper.

We implement smart-HOP in TinyOS 2.0.2 and use telosB motes for the evaluation. The transmission period of the beacon and data packets is 10 ms. This value is close to the maximum rate possible considering the processing, propagation and communication delays. The idea behind choosing the maximum data rate is to evaluate smart-HOP for scenarios with demanding QoS requirements.

Four APs are located at each corner of the deployment, and up to six more APs are randomly placed to assess the impact of APs density. To test smart-HOP under demanding conditions, we have to identify a transmission power that provides a minimum overlap among access points[5]. For our settings, $p_{out} = -20$

[5] In practice, scenarios with real-time constraints may have a higher density of APs.

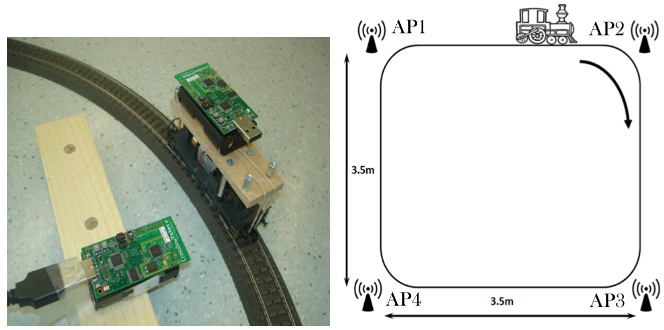



**Fig. 3.** (a) MN passing by an AP, (b) nodes' deployment

dBm satisfies this condition. Then, we run several laps with the mobile node broadcasting packets. The broadcast laps were run at different times of day, during several days and with different number of people in the room. In all these scenarios, the mobile node requires four handoffs on each lap, the time of day and number of people in the room (1 to 4 persons) do not seem to have a major impact on the number of handoffs.

We utilize interference-free channels to calibrate the parameters. The noise floor is constant around -94 dBm. Our evaluation focuses on the impact that the handoff parameters has on three network metrics:

**Packet delivery ratio:** the delivery rate of smart-HOP is compared to the best possible solution: naive broadcast. In a broadcast scenario, a packet can be received by any AP and there is no time used on handoffs.

**Number of handoffs:** this metric captures the effectiveness in avoiding pin-pong effects. The careful design of our testbed provides a constant reference to evaluate this metric: 4 handoffs per lap.

**Mean handoff delay:** it represents the average time spent to perform the handoff. Given that smart-HOP performs hard handoffs, nodes can not send packets during this time. Hence, this delay should be minimized.

### 4.2 Thresholds, hysteresis margin and AP stability

The first step in a handoff scheme is to determine when should a node deem a link as weak and start looking for another AP. In our framework this is represented by $TH_{low}$. In the sensor networks community, the *de-facto* way to classify links is to use the connected, transitional and disconnected regions. In order to identify these regions, we gathered RSSI and SNR values at different parts of the building utilizing different nodes. Figure 4 depicts these three regions for RSSI, which agree with previous studies [16]. The SNR parameters are used in the next section, when smart-HOP is evaluated under interference. The SNR is calculated by measuring the noise floor immediately after receiving the packet, and then, subtracting it from the RSSI value. The RSSI regions can be mapped directly to the SNR ones by subtracting the average noise floor.

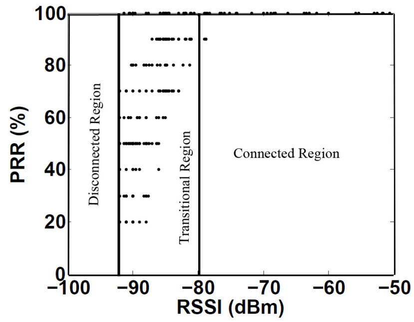



**Fig. 4.** The connected, transitional and disconnected regions in our scenario. smart-HOP performs the handoffs within the transitional region.

An educated guess for the width of the hysteresis margin could be obtained from Figure 4 (based on the 10 dB width of the transitional region). However, while this value would guarantee that *all* links above $TH_{high}$ are reliable, it would also increase the amount of beacons and time required to reach $TH_{high}$. In order to evaluate this region extensively, we consider different values for each handoff parameter, as shown in Table 1. For example, if we consider scenario $A$ with a 5 dBm margin and stability 2, it means that after the mobile node detects an AP above $TH_{high} = -90$ dBm, the node will send two 3-beacon bursts to observe if the link remains above $TH_{high}$. The hysteresis margin $HM$ captures the sensitivity to ping-pong effects, and the number of bursts $m$, the stability of the AP candidate (recall that each burst in $m$ contains three beacons).

**Table 1.** Description of second set of scenarios

| Scenarios | $TH_{low}$ | $HM$ | $m$ | Scenarios | $TH_{low}$ | $HM$ | $m$ |
|---|---|---|---|---|---|---|---|
| A | -95 dBm | 1, 5 dBm | 1, 2, 3 | C | -85 dBm | 1, 5 dBm | 1, 2, 3 |
| B | -90 dBm | 1, 5 dBm | 1, 2, 3 | D | -80 dBm | 1, 5 dBm | 1, 2, 3 |

We conduct experiments for all the scenarios in Table 1. The layout has four APs and one mobile node, as shown in Figure 3(b). For each evaluation tuple $< TH_{low}, HM, m >$, the mobile node takes four laps, which leads to a minimum of 16 handoffs. The experiments provide some interesting results. First, we will show the results for the narrow margin (1 dBm), and then the ones for the wide margin (5 dBm).

### 4.3 Observations

**The high variability of low-power links can cause severe ping-pong effects**. Figure 5(a) depicts the total number of handoffs for the narrow margin case. We observe two important trends. First, all scenarios have ping-pong effects. The optimal number of handoffs is 16, but all scenarios have between 32 and 48. Due to the link variability, the transition between neighboring APs requires between 2 and 3 handoffs. Second, a longer monitoring of stability $m$

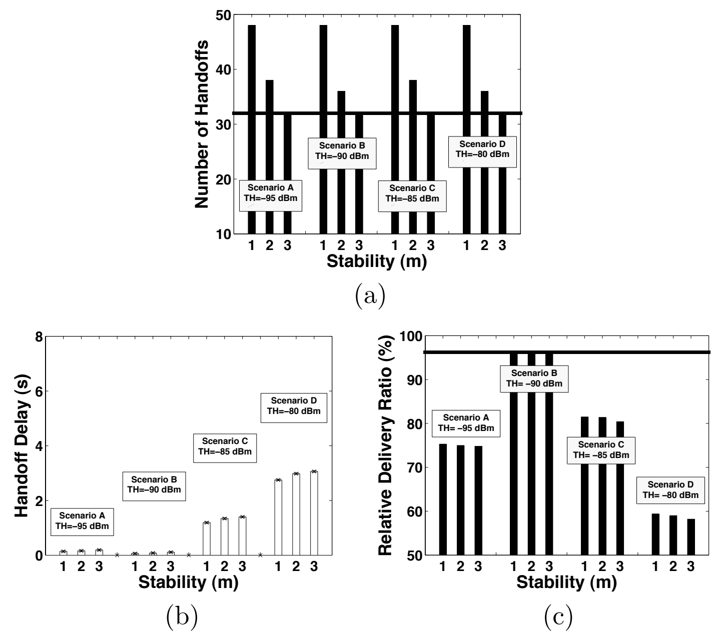



**Fig. 5.** Results for narrow hysteresis margin ($HM = 1dBm$). (a) number of handoffs, (b) mean handoff delay, (c) relative delivery ratio. The horizontal lines represent the results for the best scenario: 32 for the number of handoffs and 96 for the relative delivery ratio. These values will be used as a reference in Figure 6.

helps alleviating ping-pong effects. We observe that for all scenarios the higher the stability, the lower the number of handoffs.

**Thresholds at the higher end of the transitional region lead to longer delays and lower delivery rates**. Figure 5(b) depicts the average handoff delay for various thresholds $TH_{low}$. A threshold selected at the higher end of the transitional region (-85 or -80 dBm, scenarios C and D) can lead to an order of magnitude more delay than a threshold at the lower end (-90 dBm, scenario B). This happens because mobile nodes with higher thresholds spend more time looking for overly reliable links (more time on discovery phase), and consequently less time transmitting data (lower delivery rate). Figure 5(c) depicts the relative delivery rate and captures this trend. In order to have a reference for the absolute delivery rate, we measured several broadcast scenarios considering a high transmission rate and a 4-access point deployment. We found that the average delivery rate was 98.2%, with a standard deviation of 8.7. This implies that there are limited segments with no coverage at all. Furthermore, the overlap is minimal which tests the agility of the handoff mechanism (as opposed to dense deployments, where very good links are abundant). Scenario A in Figure 5(c) is an exception, because it remains disconnected for some periods of time. As shown in Figure 4(a), no link goes below -95 dBm, hence, when this

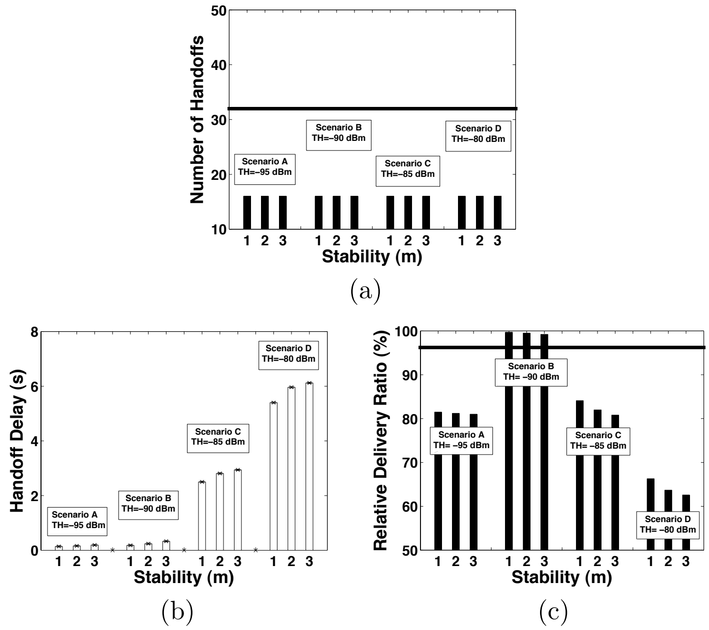



**Fig. 6.** Results for wide hysteresis margin (HM=5 dB). (a) number of handoffs, (b) mean handoff delay, (c) relative delivery ratio. The horizontal lines represent the best results obtained for HM=1. The lines highlight the importance of an accurate calibration of the handoff parameters.

threshold is used, the discovery phase does not start because the link goes below $TH_{low}$, but because disconnection time-outs occur.

**The most efficient handoffs seem to occur for thresholds at the lower end of the transitional region and a hysteresis margin of 5 dBm.** Figure 6 shows that scenario B (-90 dBm) with stability 1 maximizes the three metrics of interest. It leads to the least number of handoffs, with the lowest average delay and highest delivery rate. It is important to highlight the trends achieved by the wider hysteresis margin. First, the ping-pong effect is eliminated in all scenarios of Figure 6(a). Second, contrarily to the narrower hysteresis margin, monitoring the stability of the new AP for longer periods ($m = 2$ or 3) does not provide any further gains, because the wider margin copes with most of the link variability.

**smart-HOP can reduce the communication overhead required to transmit the data of interest.** Let us assume a simple terminology to depict the communication overhead of smart-HOP. Denoting $t_x$, $r_x$ and $c$ as the transmission cost, reception cost and average number of APs available; for every data packet sent, the cost of broadcast is $t_x + cr_x$, and the cost of smart-HOP is $(t_x + r_x)(\frac{WS+1}{WS})$. Some simple manipulations lead to the following condition $smart - HOP_{cost} > Bcast_{cost}$ if $(WS \times c - WS - 1)r_x < t_x$, that is, for smart-HOP to be less efficient than broadcast, two conditions are required: (i) a low density of APs and (ii) a high transmission cost compared to the reception cost. In practice, transmission and reception costs for the CC2420 radio are rather similar, and hence, smart-HOP is expected to be more efficient than broadcast.

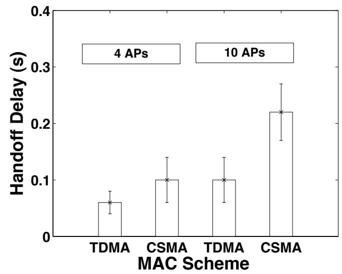



**Fig. 7.** mean handoff delay for CSMA and TDMA (Scenario B)

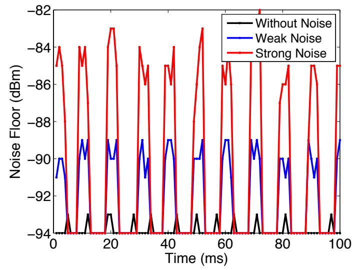
**CSMA or TDMA.** smart-HOP runs a simple TDMA MAC on the APs in order to avoid collisions and reduce the handoff delay. Each AP performs a simple modulo operation on its unique *id* to obtain a specific time slot. For example, using 10 as the modulo operator, if a mobile node has neighboring access points with id's 16, 23, 45 and 72, the selected TDMA slots are 6, 3, 5 and 2, respectively. In theory, two nodes could collide, for example APs with *id*s 14 and 24 would select the same time slot 4, in practice, clock drifts and a relatively low density of access points ($\leq$10) makes this unlikely. In our evaluation the modulo operator is 10 and the time slots are of length 5 ms (i.e., a TDMA cycle of 50 ms)[6].

We compared the default carrier sense multiple access (CSMA/CA) MAC with the TDMA-based protocol for low densities (4 APs) and high densities (10 APs). The 6 additional APs were deployed randomly in the experimental area. Figure 7 shows that for scenario B with 10 APs, the TDMA approach decreases the mean handoff delay by half. For scenarios C and D (results not shown), the type of MAC used does not play a role because the handoff delays are already high (in the order of seconds).

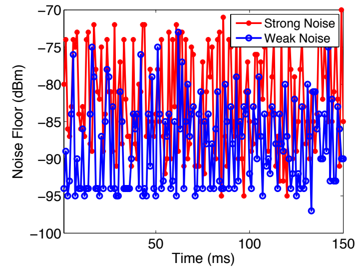
## 5 Impact of Interference: RSSI vs. SNR based handoffs

The performance of wireless networks is widely affected by radio interference. Evaluating these effects is particularly important for WSN because they operate in the unlicensed ISM bands. The congestion of radio spectrum in these bands is ever increasing due to several devices operating in them, ranging from WiFi APs to baby monitors and microwaves. In safety-critical applications, where information should be transfered in a timely and reliable way, it is a must to evaluate the impact of interfering devices. We evaluate the performance of smart-HOP under different types of interference, and find that, unless the interference

[6] It is important to notice that this simple TDMA scheme is dynamic and can work on multi-hop networks. However, in most real time scenarios, the density of APs should permit mobile nodes to have direct connectivity with at least one AP (i.e., single-hop communication)




(a)




(b)

**Fig. 8.** Noise floor for (a) periodic interference and (b) bursty interference

is bursty, strong and continuous (extreme adverse effects), smart-HOP copes well with interference.

When interference is likely to occur, smart-HOP should utilize SNR-based parameters instead of RSSI. This change of parameters is not a minor tradeoff. Utilizing SNR implies that after receiving each packet, a node should sample the noise floor and subtract this value from the RSSI. Performing these steps implies higher energy consumption and delay because the single-channel radio needs to be used for noise sampling (after receiving each packet). Hence, if no interference is expected, RSSI should the preferred metric for smart-HOP.

The tests are performed on channel 15 of the CC2420 radio, which is affected by different sources of radio interference in 2.4 GHz such as WiFi devices, Bluetooth and microwave oven. In order to perform a systematic evaluation, we utilize the most common types of interferences found in the ISM band as reported in [17], these types of interference are:

*Periodic interference*. This interference is usually spatially localized and has a regular duty cycle. The best examples are microwave ovens. We recreate this interference utilizing the Jamlab tool [17], which leverages regular motes to generate customizable interference patterns. The power level of the interference is set to (-22 dBm), the period is 10 ms and the duty cycle is 50%. In our evaluation, we place the interferer mote at the left side of the deployment. This location affects mainly APs three and four (Figure 3(b)). To test different interference levels, we place the interferer at 1m from the APs (strong interference) and 3m (weak interference). The noise pattern for AP three is shown in Figure 8(a).

*Bursty interference*. This interference is widespread and has a more irregular and random behavior. The best example is the interference caused by WiFi access points. To test this interference, we place a WiFi station inside the test room (strong interference) and on a different room six meters apart (weak interference). We have a laptop downloading a large file to maintain the interference for long periods of time. Figure 8(a) shows the interference observed at AP four, but the interference is similar on all APs.

Figure 9 shows the performance of smart-HOP under interference. First, let us evaluate the results for the periodic interference scenario. The main observation is that, under periodic interference, smart-HOP with SNR increases both, the average handoff delay and the delivery rate, right side of Figures 9(a)

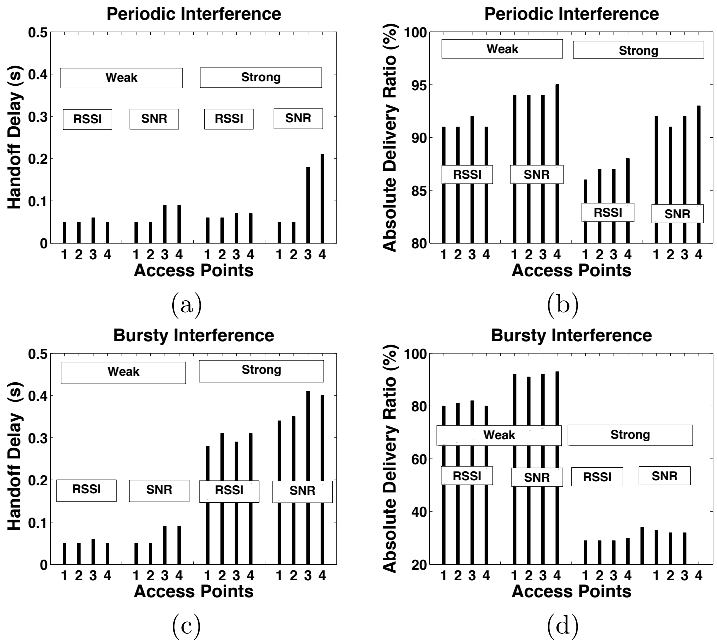



**Fig. 9.** Effects of periodic and bursty interference at each access point. Periodic: (a) mean handoff delay, (b) absolute delivery rate. Bursty: (c) mean handoff delay, (d) absolute delivery ratio

and 9(b). When SNR is used, the affected APs (3 and 4) increase their delay by a factor of 4, but the overall outcome is positive because the delivery rate increases by more than 10%. In the SNR case, the longer handoff delay occurs because mobile nodes spend more time in the discovery phase looking for links that are good in spite of interference (SNR above $TH_{high}$). On the other hand, the RSSI-based mechanism may connect faster but to weaker APs (because RSSI alone can not recognize the presence of interference). The higher delivery rate occurs because the SNR-based smart-HOP detects the presence of interference earlier and starts the discovery phase. On the other hand, RSSI-based handoffs only react when packets are lost, and once they find a new AP, the link may not be strong enough for communication (again, because RSSI can not detect interference by itself).

The bursty evaluation, Figures 9(c) and 9(d), highlights the effects of strong, bursty and continuous interference. In this scenario, the absolute delivery rate is low. However, it should be mentioned that this is not a limitation of smart-HOP, but a fundamental limitation of the low-power links utilized in WSNs. The broadcast scenario (an ideal one), does not achieve much more than smart-HOP. In fact, the *relative* delivery rate of smart-HOP with respect to the broadcast scenario is above 95%.

## 6 Related work

Handoff mechanisms have been widely studied in cellular networks [5–9] and wireless local area networks [10–12, 18], but it has not received the same level of attention in WSN.

In cellular networks, the handoff decision is centralized and typically coordinated by a powerful base station which is able to leverage considerable information about the network topology and client proximity [5]. Cellular networks also take advantage of sophisticated CDMA radios to perform soft handoff techniques [6]. The major challenge in cellular networks with handoff support is the *call dropping* effect during an ongoing call while switching between base stations [7]. A similar event occurs due to the lack of available channel –so-called *call blocking*-. In [9], some channels are exclusively allocated to handoff calls, also known as *guard channels*. In [8], a queuing strategy has been applied to delay the handoff calls until a channel becomes available. Contrary to these resourceful systems, WSNs have constrained energy resources and simple single-channel radios, which require different solutions.

Contrary to cellular systems, WiFi networks have a distributed architecture, where mobile nodes have no a-priori knowledge of the local network [10, 11]. While cellular systems require a continuous monitoring of the signal level, WiFi-based systems monitor the signals only after service degradation. The main concern of 802.11 handoff protocols is to minimize the handoff latency for real-time applications. A handoff process in WiFi-based systems is divided into the Discovery and Reauthentication phases. The channel scanning during a Discovery phase is the most time consuming process. The authors in [18] propose a MAC layer with fast handoff which uses selective scanning and records the scan results in AP's cache. When a MN moves to a location visited before, it pings the nearby APs for their available channels. In [12], each AP records the neighboring AP's information in a *neighbor graph* data structure. Then the AP can inform MN about which channels have neighboring APs. The MN needs to scan only those channels.

The key difference between WiFi and WSN handoffs is that in WiFi multiple radios are used to reduce the handoff latency while in WSN applications a single radio is used. In WSN, a centralized handoff approach is not feasible as it incurs a high overhead on the system. Handoffs in sensor networks should be distributed –similar to WiFi networks– while using a single-channel radio that focuses on the up-link and that can cope with the high variability of low power links.

There are only a few studies on handoffs in WSN and they focus on some basic guidelines but do not perform empirical tests [19–21]. The most relevant study to smart-HOP is presented in [4], which describes a wireless clinical monitoring system collecting the vital signs of patients. In this study, the mobile node connects to a fixed AP by listening to beacons periodically broadcasted by all APs. The node connects to the AP with the highest RSSI. The scheme is simple and reliable for low traffic data rates. However, there is a high utilization of bandwidth due to periodic broadcasts and handoffs are passively performed once the mobile node can not deliver packets. smart-HOP eliminates the use of periodic broadcasts and allows mobile node to *actively* look for the best handoff opportunities.

A reliable handoff depends significantly on the link quality estimator used to monitor the link. Different link quality estimators have been proposed for sensor networks. They apply different criteria to estimate the link status, such as RSSI, SNR, LQI or link asymmetry [22, 23]. In our case we use a simple and fast sampling of RSSI and SNR which have been shown to provide reliable metrics [14, 24]

## 7 Conclusions and Future Work

This paper addresses the design, implementation and validation of a reliable and timely handoff mechanism for mobile WSNs. The handoff mechanism is required for application such as health-care monitoring where sensors collect the vital signs of various patients. Any disconnection or long network inaccessibility times would have serious consequences. Indeed, the correctness of the application depends greatly on the proper management of mobility to ensure connectivity and real-time streaming. The use of an adequate handoff mechanism becomes an important requirement for such an application.

Compared to traditional cellular and WiFi systems, sensor nodes performing handoffs face two challenges: (i) their constrained resources limit the use of more sophisticated handoff techniques and (ii) their simple and low-power radio transceivers lead to highly variable wireless links, which affects the stability of the handoff process.

The contribution of our work is smart-HOP, a handoff mechanism based on well-known techniques from wireless communication, but calibrated to suit the demands of mobile WSN applications. We perform a carefully designed set of experiments, based on IEEE 802.15.4 radios, to get a better insight on the settings of key parameters, namely, the lower link quality threshold level (required to start the handoff, -90 dBm) and the hysteresis margin (required to finalize the handoff and for stability, 5 dBm).

**Future Work.** Our work is at an initial phase and smart-HOP should be further analyzed to validate the parameters obtained in our study. There are three directions that are particularly necessary to investigate. First, the optimal window size for lower traffic rates. If the application does not require strict real-time constraints, the sampling frequency of the channel may need to be re-evaluated to trade-off energy consumption and delivery rate. Second, the generality of the hysteresis margin. We hypothesize that the hysteresis margin is only platform-dependent. That is, as long as the same radio chip is used, the hysteresis margin should lead to similar performances in other indoor and outdoor scenarios. If this hypothesis does not hold, smart-HOP would require pre-deployment measurements to identify the optimal thresholds. Third, a more realistic scenario, with people carrying motes across different rooms, should be evaluated to capture the blocking effects of the human body (no line-of-sight) and different speeds.

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