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Reliable and fast hand-offs in low-power wireless networks (extended paper)

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Abstract

Hand-off (or hand-over), the process where mobile nodes select the best access point available to transfer data, has been well studied in wireless networks. The performance of a hand-off process depends on the specific characteristics of the wireless link. In the case of low-power wireless networks, hand-off decisions must be carefully taken by considering the unique properties of inexpensive low-power radios. This article addresses the design, implementation and evaluation of smart-HOP, a hand-off mechanism tailored for low-power wireless networks. This work has three main contributions. First, it formulates the hard hand-off process for low-power networks (such as typical wireless sensor networks -WSNs) with a probabilistic model, to investigate the impact of the most relevant channel parameters through an analytical approach. Second, it confirms the probabilistic model through simulation and further elaborates on the impact of several hand-off parameters. Third, it fine-tunes the most relevant hand-off parameters via an extended set of experiments, in a more realistic experimental scenario. The evaluation shows that smart-HOP performs well in the transitional region while achieving more than 98% relative delivery ratio and hand-off delays in the order of a tenth of a second.

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Abstract

Hand-off (or hand-over), the process where mobile nodes select the best access point available to transfer data, has been well studied in wireless networks. The performance of a hand-off process depends on the specific characteristics of the wireless link. In the case of low-power wireless networks, hand-off decisions must be carefully taken by considering the unique properties of inexpensive low-power radios. This article addresses the design, implementation and evaluation of smart-HOP, a hand-off mechanism tailored for low-power wireless networks. This work has three main contributions. First, it formulates the hard hand-off process for low-power networks (such as typical wireless sensor networks -WSNs) with a probabilistic model, to investigate the impact of the most relevant channel parameters through an analytical approach. Second, it confirms the probabilistic model through simulation and further elaborates on the impact of several hand-off parameters. Third, it fine-tunes the most relevant hand-off parameters via an extended set of experiments, in a more realistic experimental scenario. The evaluation shows that smart-HOP performs well in the transitional region while achieving more than 98% relative delivery ratio and hand-off delays in the order of a tenth of a second.

Index Terms

Mobility, Low-power links, Wireless sensor networks, Link characteristics, hand-off, hand-over.

I. INTRODUCTION

Wireless technologies are enabling an expanding range of mobile applications, building not only on smart phones and tablets, but also on wearable sensors, industrial machinery, health-monitoring instruments and robotics [1]. These devices play a key role in many new application domains that push wireless networks to dramatically improve quality-of-service properties such as throughput, timeliness, reliability, security, privacy, usability, and

efficiency [1]–[3]. These QoS requirements must be guaranteed between mobile nodes and also between mobile nodes and fixed network infrastructures.

A recent NSF report [1] presents an exemplary scenario capturing this situation. In the future, in-body sensors collecting “*aggregated data from the entire population can predict outbreaks of epidemics even before they occur*” and it further states that “*such applications require in-body sensors that not only have robust wireless connectivity, but also are highly energy-efficient*”. We can easily foresee a hospital covered by a wireless sensor network (WSN) infrastructure (used for one or more purposes). Patients use body sensors networks to monitor relevant/vital signs – they are monitored and tracked either when standing still or moving (walking, wheel chair or in bed). Doctors and medical staff also use body sensor networks, which can be used to measure their stress/anxiety levels and also to track and warn them about emergency situations. Only if these wearable body sensor nodes are able to communicate reliably and in real-time this could effectively transform medical services in the near future.

In industrial environments such as factory automation and process control, it is essential to monitor the actual state of components and machines in a continuous manner. The Factories of the Future 2020 roadmap [2] forecasts “*the need for advanced machine interaction with humans through ubiquity of mobile devices to receive relevant production information*”. Such type of systems is also expected to detect potentially dangerous conditions in real-time and launch necessary countermeasures to prevent their impact on workers’ health and safety.

The Cooperating Objects roadmap [3] envisions and outlooks several application domains requiring the cooperation between mobile robots instrumented with sensing/actuation capabilities with fixed wireless sensor nodes, such as for search & rescue, environment exploration and surveillance applications. A large number of small (and inexpensive) robots can cooperate to tackle a large problem. These swarms of robots pose important challenges to robot designers as their cooperative behavior is not as simple to program as a single robot: many algorithms are distributed and rely heavily on communication between the participating members of the swarm and also with a fixed wireless infrastructure. Typically, this communication is time-critical, meaning it has to be completed within a time deadline to be effective.

Many recent research projects (e.g. [4]–[7]) and research works (e.g. [8]–[12]) have considered network architectures that require real-time (or at least continuous) data collection from mobile nodes through low-power wireless interfaces to fixed network infrastructures. In oil refineries, workers are exposed to hazardous environments in highly critical areas, so collecting the workers’ vital signs during their daily activity enables to quickly detect abnormal situations [8]. In clinical monitoring, patients have embedded sensing devices that report real-time streams of information through a fixed infrastructure [9], [10]. Mobile robots are also used to assist fixed sensor network deployments in wildlife monitoring to detect and extinguish fire [11], [12].

The communication between mobile nodes and a fixed infrastructure has been extensively studied in Cellular and WiFi networks, and it has been addressed through the use of hand-off mechanisms. However, these methods cannot be readily applied to low-power wireless networks [13]. First, Cellular and WiFi networks have more sophisticated radios with more energy resources. This means that their wireless links are much longer and more reliable than those provided by low-power low-cost radios, and hence the thresholds and parameters associated to hand-off mechanisms

need to be tuned accordingly. Second, base stations in cellular networks build on fixed wired infrastructures with strong processing and communication capabilities, which is usually not applicable in low-power networks. Third, mobile nodes in Cellular and WiFi networks are usually in the coverage range of several strong radios while the unreliable links of low-power wireless networks have little overlap.

In this paper we address the design, implementation and evaluation of smart-HOP, a hand-off mechanism that considers the specific features of low-power links to enable fast, reliable and efficient hand-offs. We enhance our preliminary work published at [13] with the following new contributions:

- 1) We formulate a hard hand-off process for low-power networks with a probabilistic model to study the impact of relevant channel parameters.
- 2) We design a simulation model to confirm the probabilistic analysis and also to analyze the impact of relevant network parameters on the overall performance.
- 3) We further fine-tune the hand-off parameters through an extensive set of experiments in a realistic environment with a person holding the mobile node.

Organization. In Section II, we explain the main limitations of low-power networks and overview some hand-off approaches for low-power wireless networks. In the remainder of the paper, the terms low-power wireless networks and wireless sensor networks are used interchangeably. In Section III, we describe the smart-HOP mechanism and its main parameters, and illustrate some experimental results obtained in a controlled environment. The analytical and simulation models together with an extensive study of the impact of channel parameters are presented in Section IV. In Section V, we provide the best parameter tuning based on an extensive experimental analysis in a realistic environment. Related work is outlined in Section VI. Finally, we conclude the paper and discuss our most relevant findings in Section VII.

II. PROBLEM STATEMENT

This section elaborates on the need to calibrate hand-offs according to the particular characteristics of low-power wireless networks and on the parameters that should be taken into account when designing a hand-off mechanism.

A possible naive solution to support mobility in WSNs is for mobile nodes to broadcast messages to all access points (APs) in their vicinity. The broadcast approach, while simple, has a major limitation: broadcasts lead to redundant information at neighboring APs (since more than one AP may receive the same packet). This implies that the fixed infrastructure has to either waste resources in forwarding the same information to the end point, or to use a complex scheme, such as data fusion, to eliminate duplicated packets locally.

A more efficient solution is for mobile nodes to select a single AP to transmit data at any given time. This alternative requires nodes to perform hand-offs between neighboring APs. *Hand-off refers to the process where a mobile node disconnects from one AP and connects to another AP.* Hand-offs have been extensively studied in other wireless systems [14]–[18], in particular Cellular and Wireless Local Area Networks (WLANs). However, these techniques are proven to be unsuitable for low-power wireless networks [19]. Even nowadays, cellular companies perform exhaustive radio surveys at different points of a city to improve the hand-off performance of their mobile

users [20], [21]. Our study follows this line of work, but on the uncharted territory of WSNs. Contrary to more powerful wireless systems, such as cellular networks, which have typically advanced spread spectrum radios and high energy resources, WSNs have severely constrained resources. Hence, we need a better understanding of the hand-off process in low-power wireless networks.

Limitations of low-power links. Low-power links have two characteristics that affect the hand-off process: short coverage and high variability [22], [23]. Short coverage derives from a low density of access points. In cellular networks, for example, it is common for a mobile node to be within the range of tens of APs. This permits the mobile node to be conservative with the hand-off thresholds, because it is very likely to encounter good quality links. On the other hand, low-power wireless networks may not be deployed in such high densities, and hence the hand-off should relax its link quality requirements. In practice, this implies that the hand-off parameters should be more carefully calibrated within the (unreliable) transitional region [13]. Several empirical studies revealed the existence of three distinct reception regions in a wireless link; connected, transitional, and disconnected [24], [25]. The transitional region is often quite significant in size, and is generally characterized by high variance in reception rates and asymmetric connectivity. In WSN applications, most of the links (more than 50% [22]) are in the transitional region.

Several empirical studies show that WSN links have high unreliability in dense deployments [26], [27]. The high variability of links has a direct impact on the stability of hand-offs. When not designed properly, hand-off mechanisms may degrade the network performance due to the *ping-pong* effect, which consists in mobile nodes having consecutive and redundant hand-offs between two APs due to sudden fluctuations of their link qualities. This usually happens when a mobile node moves in the vicinity of two APs. Hence, to effectively cope with link instability, a hand-off mechanism should calibrate the appropriate thresholds, taking into account the variance of the wireless links.

Figure 1 illustrates this issue and depicts the three common wireless regions [24]. We collected the received signal strength (RSSI), signal-to-noise ratio (SNR) and their respective packet reception ratio (PRR) at different locations of an indoor environment with different sensor nodes [13]. 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.

The transitional region for wireless nodes using the CC2420 radio transceiver encompasses the approximate range [-92 dBm, -80 dBm] (shown in Figure 1(a)). Intuition may dictate that the hand-off should be performed within the connected region as it indicates more reliable links. In practice, a hand-off should start when the link with the current (serving) AP drops below a given value (TH_{low}) and should stop when it finds a new AP with the required link quality (above TH_{high}).

Figure 2(a) depicts an example of inefficient hand-off and illustrates the negative impact of this conservative approach. In this scenario, the lower threshold is set to -85 dBm, and the upper threshold is set to 1 dBm higher. This particular choice of parameters results in three undesirable consecutive hand-offs between the two contiguous APs (three shadowed vertical bars), which we refer to as the *ping-pong effect* and that results in a long network

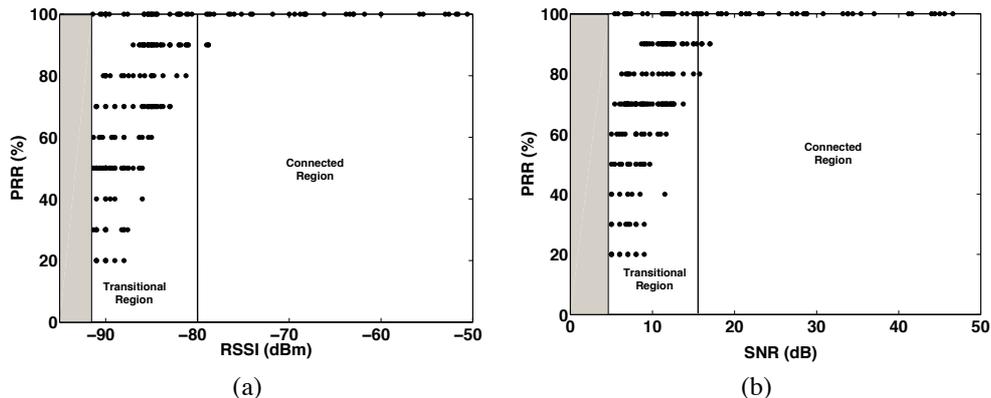


Fig. 1. Low-power link model (a) RSSI vs. PRR. For RSSI greater than -80 dBm, the PRR is greater than 90%, and for RSSI less than -92 dBm, the PRR is less than 10%. In between, a small variation in the RSSI can cause a big difference in the PRR, which is identified as transitional region. (b) SNR vs. PRR. The borders for SNR are 4 dB and 16 dB [13].

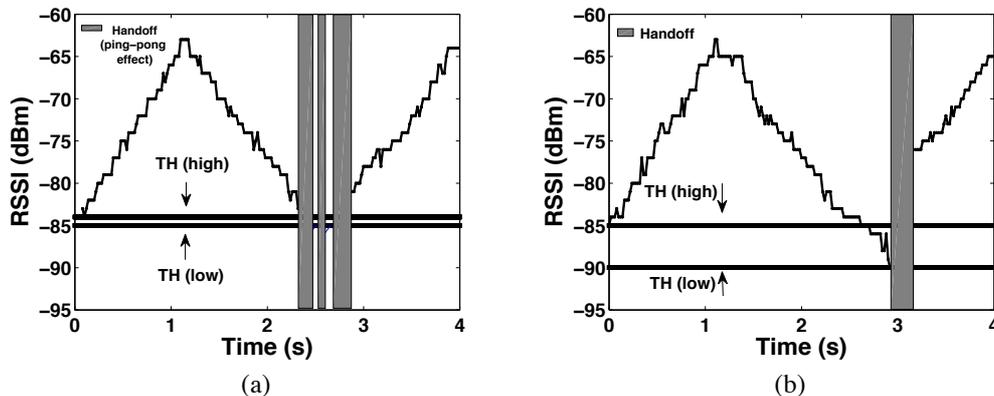


Fig. 2. (a) an example of inefficient hand-off with narrow *hysteresis margin* (1 dBm), $TH_{low} = -86$ dBm and $TH_{high} = -85$ dBm, resulting in three consecutive hand-offs (ping-pong effect). (b) an example of an efficient hand-off with wide *hysteresis margin* (5 dBm), $TH_{low} = -90$ dBm and $TH_{high} = -85$ dBm, resulting in a single hand-off [13].

inaccessibility time (700 ms). Increasing the threshold margin to 5 dBm (as illustrated in Figure 2(b)) eliminates the ping-pong effect (one shadowed vertical bar only) and hence reduces the hand-off delay to approximately 200 ms. This simple example shows that studying the low-power link characteristics is paramount for obtaining efficient hand-off processes.

Hard or soft hand-off for WSNs. Hand-offs are classified into two main classes: hard hand-offs and soft hand-offs [28]. In a *soft hand-off*, the radio can use multiple radio 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 hand-off radios is Code Division Multiple Access (CDMA) [29]. WSN nodes usually do not have a sophisticated radio and have far less resources in terms of bandwidth, energy and processing. It is also possible to perform soft hand-offs by utilizing a network-based mobility management mechanism; e.g. as supported by mobile IPv6. Moreover, the use of IPv6 imposes extra overhead and increases the energy consumption of the network drastically, which is not admissible in most WSN applications.

In a *hard hand-off*, the radio can use only one channel at any given time, and hence it needs to stop the data

transmission before the hand-off process starts. Consequently, in hard hand-offs 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 WSNs should follow a hard hand-off approach.

III. BASICS ON THE SMART-HOP

In this section, first we explain the data communication between the MN and a fixed infrastructure of APs, according to the smart-HOP procedure. Then, we highlight the importance of three parameters: *link monitoring*, *hysteresis threshold* and *stability monitoring*. Afterward, we compare the cost of communication in the smart-HOP with other conventional hand-off approaches. The evaluations of the experiments in a controlled environment (model train moving in a square track) are then discussed.

A. The smart-HOP algorithm

The smart-HOP algorithm has been proposed in [13]. The algorithm has two main phases: (i) *Data Transmission Phase* and (ii) *Discovery Phase*. A timeline of the algorithm is depicted in Figure 3.

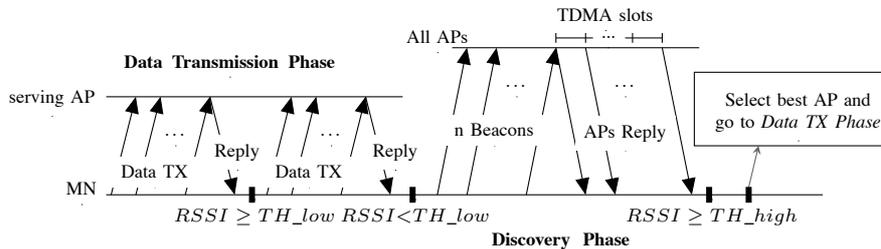


Fig. 3. Timing diagram of the smart-HOP mechanism [13].

For the sake of clarity, let us assume that a node is in the *Data Transmission Phase*¹. In this phase, the mobile node is assumed to have a reliable link with an AP, defined as serving AP in Figure 3. The mobile node monitors the link quality by receiving *reply* packets from the serving AP. Upon receiving n data packets in a given window, the serving AP replies with the average RSSI or 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. It is important to notice that the 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, that AP is simply not part of the process. The smart-HOP process relies on three main parameters presented in detail as follows.

Parameter 1: *link monitoring*. It determines how frequent the *link monitoring* should be. The *link monitoring* property is captured by the Window Size parameter (ws), which represents the number of packets required to estimate the link quality over a specific time interval. Considering an inter-packet interval of 5 ms with $ws=3$,

¹smart-HOP has a simple initialization phase that is similar to the *Discovery Phase*.

results in *link monitoring* of 66 Hz^2 . 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. The packet delivery reduces as the MN opts for performing some unnecessary hand-offs. The hand-off is triggered by detecting low quality links, resulting from the decrease of the signal strength. 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, which is not suitable for mobile networks with dynamic link changes.

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 ($TH_{high} \stackrel{\text{def}}{=} TH_{low} + HM$, where HM is the *hysteresis margin*). The optimal values for the lower threshold level and the *hysteresis margin* are defined through experimental tests as shown in Section V. During the *Discovery Phase*, the mobile node sends ws beacons periodically, and the neighboring APs reply with the average RSSI or SNR of the received beacons. If one or more APs are above TH_{high} , the mobile node connects to the AP with the highest link quality and resumes data communication, else, it continues broadcasting beacons in bursts until discovering a suitable AP. In order to reduce the effects of collisions, the APs use a simple TDMA MAC. Our studies enclose that the smart-HOP running a TDMA-based MAC reduces hand-off delay compared with a CSMA-based MAC due to the collision avoidance feature of a TDMA-based scheme³.

Parameter 2: threshold levels 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 thresholds should be selected according to the boundaries of the transitional region. The transitional region is often quite significant in size and hence a large number of links in the network (higher than 50%) are unreliable [30], [31]. Therefore, wireless nodes are likely to spend most of the time in the transitional region.

A tight estimation of the threshold level within the transitional region is obtained from experimental analysis. If the TH_{low} threshold is too high, the node could perform unnecessary hand-offs (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 variability of low-power wireless links. If the *hysteresis margin* is too narrow, the mobile node may end up performing unnecessary and frequent hand-offs between two APs (ping-pong effect), as illustrated in Figure 2. If the *hysteresis margin* is too large, hand-offs may take too long, which ends up increasing the network inaccessibility times, and thus decreasing the delivery rate.

Parameter 3: stability monitoring (m). 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 handing-off to that AP. In order to avoid this, it is important to assess the stability of the candidate AP. After detecting an AP with the link quality above TH_{high} , the MN sends m further bursts of beacons to check the stability of that AP. The burst of

²In the extended experiments, the beacons' interval increased to 10 ms. The longer period in transmitting beacons increased the chance of beacon reception at the APs. In the *Data Transmission Phase*, after sending a burst of beacons, the MN waits for 10 ms to receive the reply from the serving parent. In the *Discovery Phase*, the waiting time is increased to 100 ms in order to get replies from all neighbor APs.

³smart-HOP has been designed in a protocol-agnostic way. The idea is to be able to integrate smart-HOP in any MAC/routing protocol, with no or minimum modifications.

beacons stands for the ws request beacons followed by the reply packets received from the neighboring APs. As can be easily inferred, the *stability monitoring* and the *hysteresis margin* parameters are tightly coupled. A wide *hysteresis margin* requires a lower m , and vice-versa. In the experimental evaluation (Section V), we will show that an appropriate tuning of the *hysteresis margin* will lead to $m = 1$.

B. Why smart-HOP for WSNs?

Hand-offs are used in all wireless mobile networks. This simple concept of switching from one AP to another requires very careful design considerations, so that the application requirements and system limitations are respected. In this subsection, first we outline the main features of hand-off processes in Cellular and WiFi networks, and show that a new approach is required for low-power wireless networks —smart-HOP, comparing the communication cost of these hand-off approaches.

In cellular networks, the base stations have high energy, processing, and communication resources. All the APs are connected through a stable wired backbone, which is responsible for making hand-off decisions. All mobile nodes periodically broadcast beacons along with their data packets. At the same time, the base stations communicate with each other and assess the location and the link quality of all mobile nodes. By detecting a low quality link, the base stations decide for the next servicing base station (for the MN).

In WiFi networks, power and bandwidth are more limited than in cellular networks. Thus, performing a centralized decision at the base stations (similar to cellular networks) is not efficient. In these networks, a distributed hand-off decision is performed at the MNs. All APs periodically broadcast beacons in various available channels with a precise timing (to eliminate overlapping). The MN periodically broadcasts request packets in all channels to get immediate replies (beacons) from neighbor APs. During the *Data Transmission Phase*, the MN gets periodic beacons from the serving AP. By detecting a low quality link with the serving AP and high quality link with one of the neighbors, the MN decides for a hand-off process.

smart-HOP can reduce the communication overhead. Applying the aforementioned techniques in WSNs requires a lot of beaconing, which in turn increases the network overhead, collisions and energy consumption. In low-power low-cost wireless networks with a poor backbone of APs, a centralized approach is not feasible. On the other hand, a periodic beaconing of APs in a single radio network leads to packet collisions. smart-HOP is a distributed hand-off mechanism where MNs are responsible for broadcasting beacons after detecting a low quality link.

Let us assume a simple terminology to depict the communication overhead of smart-HOP. Denoting c_{tx} , c_{rx} , c_b , and n_{AP} as the transmission cost, reception cost, beaconing cost and average number of APs available⁴. The communication overhead of all wireless networks is formulated as follows. (i) WSNs with smart-HOP is $(c_{tx} + c_{rx})(1 + \frac{1}{ws})$, (ii) WSNs with broadcast approach is $t_x + cr_x$, (iii) WiFi networks is $(c_{tx} + c_{rx}) + (n_{AP} \times c_b + n_{AP} \times c_{rx})$, and (iv) cellular networks is $(c_{tx} + n_{AP} \times c_{rx}) + (c_b + n_{AP} \times c_{rx})$. It is important to note that in

⁴The beaconing (process of transmitting beacons) is defined separately in order to be distinguished from the data transmission (c_{tx}). However, the cost of transmitting a data packet and a beacon is assumed equal.

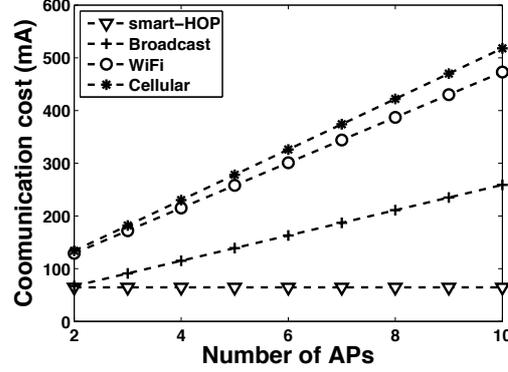


Fig. 4. The communication costs of broadcast in WSNs and the hand-off approaches in wireless networks.

estimating the costs, we considered the general concept of hand-off approaches that is common in most of the literature. Simple manipulations lead to the following conditions⁵.

- 1) $\text{smart-HOP}_{\text{cost}} > \text{Broadcast}_{\text{cost}}$ if $(ws \times n_{AP} - ws - 1)c_{rx} < c_{tx}$
- 2) $\text{smart-HOP}_{\text{cost}} > \text{cellular}_{\text{cost}}$ if $ws \times c_b + c_{rx}(2n_{AP} \times ws - ws - 1) < c_{tx}$
- 3) $\text{smart-HOP}_{\text{cost}} > \text{WiFi}_{\text{cost}}$ if $ws \times n_{AP} \times c_b + c_{rx}(n_{AP} \times ws - 1) < c_{tx}$

The only situation that verifies the above conditions is to have a very high transmission cost compared to the reception cost. In practice, transmission and reception costs for low-power radios such as the CC2420 radio are rather similar ($c_{tx} \cong c_b \cong 19$ mA and $c_{rx} \cong 24$ mA [32]). Hence, smart-HOP is expected to be more efficient than the broadcast approach in WSNs and the conventional hand-off approaches in other wireless networks. The cost of the four hand-off approaches is illustrated in Figure 4.

Architectural design. smart-HOP has some distinct design features. Most hand-off 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, WSN deployments may have a limited overlapping between neighboring APs –due to low coverage radii and low node density, and this limited overlapping 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. 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), hand-offs 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 be able to detect link quality degradation and trigger the hand-off process. This is simply done by maintaining a disconnection timeout. If the mobile node does not receive *reply* packets for a certain period of time, it starts the *Discovery Phase*.

⁵Two more conditions of $n_{AP} > 1$ (existence of more than one AP in the range of each MN) and $ws > 1$ (to apply a windowing process) are also respected.

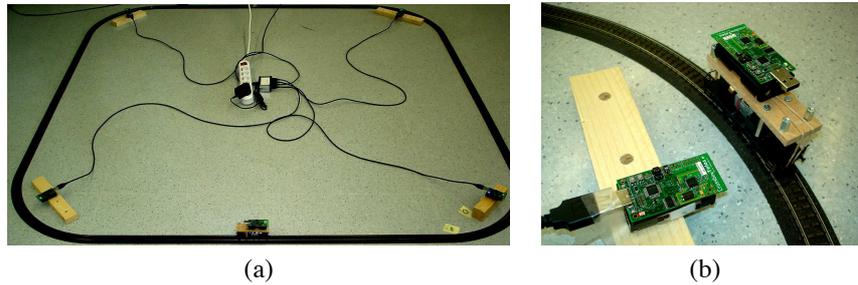


Fig. 5. smart-HOP of the preliminary experiments for assessing and tuning the smart-HOP hand-off mechanism (a) 4 APs and a MN, (b) MN passing by an AP [13].

The time-out parameter depends on the timing requirements of the application; in our case, it was set to 100 ms.

C. Test-bed setup for the preliminary experiments

The aim of the *preliminary experiments* was to investigate the feasibility of the smart-HOP mechanism in a controlled environment with limited dependencies on link dynamics.

In this way, we deployed a model-train in a large room (7 m \times 7 m) and the locomotive followed a 3.5 m \times 3.5 m square layout (an extensive description on the *preliminary experiments* is presented in [13]). The speed of the locomotive was about 1 m/s (similar to the average human walking speed). Figure 5(a) depicts the experimental scenario and Figure 5(b) shows the locomotive passing by an AP.

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 reliability and timing requirements of the application. In applications with more stringent reliability and timing requirements, such as the ones we are considering, a complete coverage is paramount. To prevent extreme deployment conditions such as very high or very low density of APs, we guaranteed a minimum overlap between neighboring APs. It was provided by choosing a proper transmission power (-20 dBm) and locating the APs far enough from each other.

The transmission period of the beacon and data packets was 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 was to evaluate smart-HOP for scenarios with more demanding QoS requirements. Four APs were located at the corners of the railway, and up to six additional APs were randomly placed, to assess the impact of AP's density.

We ran four laps with the MN broadcasting packets, in each set of experiments. The experiments were run at different times of the day, during several days and with a different number of people in the room. In all these scenarios, the mobile node required a minimum of four hand-offs in each lap. The time of the day and number of people in the room (1 to 4) did not seem to affect the number of hand-offs. We utilized an interference-free channel to calibrate the parameters (channel 15, with a constant noise-floor of -94 dBm).

Performance metrics. In a mobile network, it is crucial to maintain network connectivity as much as possible

TABLE I
DESCRIPTION OF SCENARIOS [13]

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

by minimizing the inaccessibility periods and the frequency of hand-offs. In this line, we define the following three metrics to evaluate the performance of the smart-HOP algorithm.

- 1) *Packet delivery ratio*. It defines the ratio of packets successfully delivered to the total number of packets sent.
- 2) *Number of hand-offs*. This metric helps identifying the existence of ping-pong effect. Multiple hand-offs in a single trip of a MN from one AP to another AP means that the ping-pong effect has occurred.
- 3) *Hand-off delay*. It represents the network inaccessibility time and is measured as the average time spent in the *Discovery Phase* (to find a better AP). Given that smart-HOP is a hard hand-off mechanism, nodes cannot send packets during this time; hence, this metric should be minimized.

D. Thresholds, hysteresis margin and AP stability

The first step in a hand-off scheme is to determine when should a node deem a link as weak and start looking for another AP (represented as TH_{low} in our framework). In the sensor networks community, the *de-facto* way to classify links is to use the connected, transitional and disconnected regions.

An educated guess for the width of the *hysteresis margin* could be obtained from Figure 2 (based on the 10 dBm 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 considered different values for each hand-off parameter, as shown in Table I. 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 the ping-pong effect, and the number of bursts m reflects the stability of the AP candidate (recall that each burst in m contains three beacons).

We conducted experiments for all the scenarios in Table I. The layout had four APs and one mobile node, as shown in Figure 5. The placement of the APs was in such a way to obtain minimum overlap between the links of the neighboring APs. This low density of APs enables a hand-off process between two APs located at the neighboring corners. For each evaluation tuple $\langle TH_{low}, HM, m \rangle$, the mobile node performed four laps, leading to a minimum of 16 hand-offs. In each trip from one AP to the next, an efficient scenario must perform one hand-off, which in turn leads to four hand-offs in one lap trip. The experiments provided some interesting results. First, we show the results for the narrow margin (1 dBm), and then the ones for the wider margin (5 dBm).

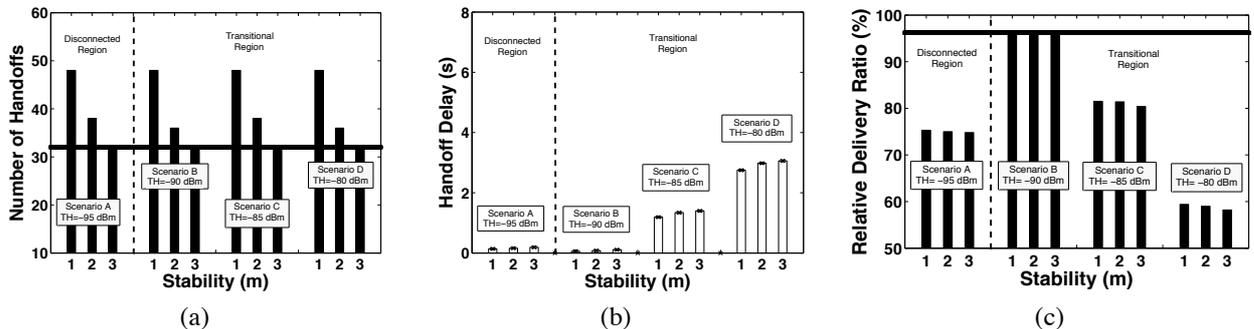


Fig. 6. Results for narrow *hysteresis margin* ($HM = 1dBm$). (a) number of hand-offs, (b) mean hand-off delay, (c) relative delivery ratio. The horizontal lines represent the results for the best scenario: 32 for the number of hand-offs and 96% for the relative delivery ratio [13].

E. Observations

The high variability of low-power links can cause severe ping-pong effect. Figure 6(a) depicts the total number of hand-offs for the narrow margin case. We observed two important trends. First, all scenarios have ping-pong effect. The minimum number of hand-offs in this scenario is supposed to be 16 (one hand-off in each trip from one AP to another). However, the figure indicates 32 to 48 hand-offs in 4-laps trip. Due to the link variability, the transition between neighboring APs requires between 2 and 3 hand-offs. Second, a longer monitoring of stability m helps alleviating the ping-pong effect. We observe that for all scenarios the higher the stability, the lower the number of hand-offs.

Thresholds at the higher end of the transitional region lead to longer delays and lower delivery rates.

Figure 6(b) depicts the average hand-off 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 (the *Discovery Phase* takes longer), and consequently less time transmitting data (lower delivery rate). Figure 6(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 hand-off mechanism (as opposed to dense deployments, where very good links are abundant). Scenario A in Figure 6(c) is an exception, because the MN remains disconnected for some periods of time. As shown in Figure 4(a), no link goes below -95 dBm, hence, when this 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 hand-offs seem to occur for thresholds at the lower end of the transitional region and a hysteresis margin of 5 dBm. Figure 7 shows that scenario B (-90 dBm) with stability 1 maximizes the three metrics of interest. It leads to the lowest number of hand-offs, with the lowest average delay and highest delivery

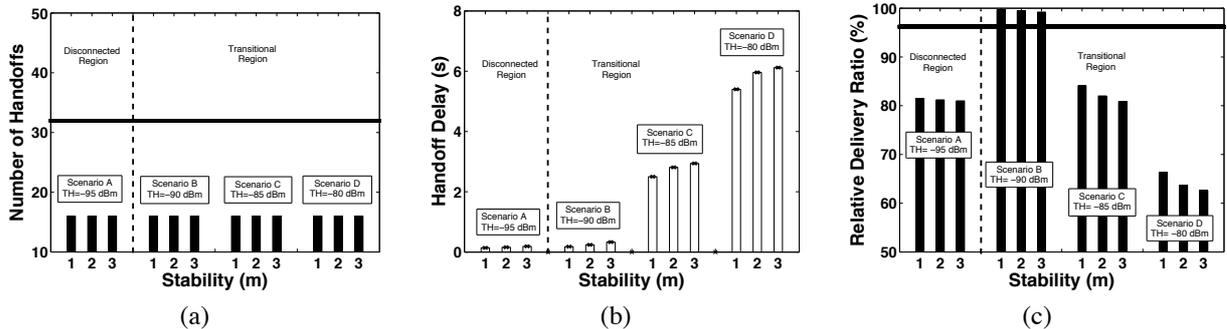


Fig. 7. Results for wide *hysteresis margin* ($HM=5$ dBm). (a) number of hand-offs, (b) mean hand-off delay, (c) relative delivery ratio. The horizontal lines represent the best results obtained for $HM=1$ dBm [13].

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 7(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.

IV. ANALYTICAL MODEL AND EVALUATION

The performance of algorithms in low-power wireless networks may greatly change depending on the network layout and environmental conditions. We conceived an analytical model for further evaluating the smart-HOP algorithm. In this probabilistic analysis, we study the impact of two major channel parameters:

- 1) *path-loss exponent* (η). It measures the power of radio frequency signals relative to distance.
- 2) *standard deviation* (σ). It measures the standard deviation in RSSI measurements due to log-normal shadowing.

The values of η and σ change with the frequency of operation and the clutter and disturbance in the environment. At this stage, we study the smart-HOP performance in various environmental conditions to observe the feasibility and efficiency of the algorithm.

In this section, first we describe the system model and the probabilistic model for a hard hand-off process in WSNs. Then, we investigate the impact of channel parameters on the hand-off performance and check the analytical results through a simulation analysis. After confirming the viability of the algorithm, we will move to more realistic experiments for better tuning the relevant parameters (Section V).

A. Probabilistic model

It is important to consider a model that is faithful to the underlying physical model while being amenable to analysis. We assume a scenario consisting of two APs (AP_a and AP_b) and a MN. This assumption is enough without loss of generality, as we are considering a hard hand-off process. In the probabilistic model, we ignore the *link monitoring* and *stability monitoring* by considering $ws=m=1$, as adding these parameters into the analysis increases the complexity of the equations and is not in the scope of our work.

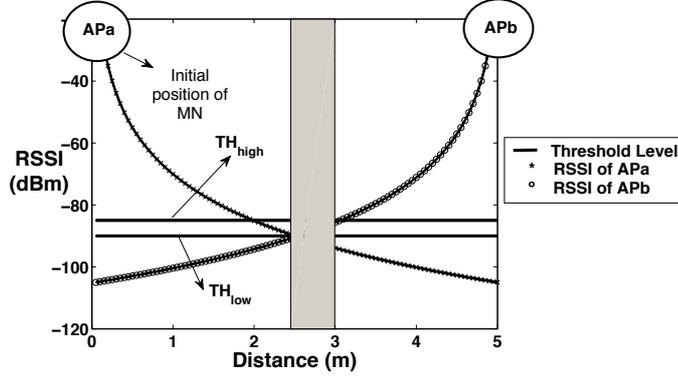


Fig. 8. System model. It show the RSSI fluctuations of AP_a and AP_b in a 10m distance. The threshold levels are assumed -85 and -90 dBm. The hand-off happens in the middle of this trip (shadow area).

The two main hand-off performance metrics are the probability of ping-pong effect and the expected hand-off delay [33]. The system model and a general behavior of smart-HOP are shown in Figure 8. The two APs are separated by distance $d(m)$ while the MN moves from the vicinity of AP_a to the vicinity of AP_b along a straight line. In this model, the MN moves with a constant speed of 1 m/s. The received signal strength from AP_a declines till it reaches the lower threshold level TH_{low} , thus triggering the hand-off process. From this point onwards, the MN stops communication with AP_a and tracks the RSSI of the neighboring AP, AP_b , (single radio eliminates the probability of collecting RSSI readings from multiple neighbor APs at the same time). If the mobile node observes a signal strength above a higher threshold level, TH_{high} , the hand-off process is considered to be finished. The hand-off period is marked with a shadowed vertical bar in Figure 8.

Link quality monitoring. There are different ways of measuring the link quality metric. In this work, we consider the RSSI as the link quality level. The probabilities of being below the lower threshold level and above the higher threshold level are defined by using a Q-function. In this turn, the traveling path of the MN is divided into a number of slots. For the sake of simplicity, we consider the same sampling rate for both the Discovery and Data Transmission Phases. These probabilities are expressed as follows.

$$P(R_a(i) < TH_{low}) = Q\left(\frac{-TH_{low} + R_a(i)}{\sigma}\right) \quad P(R_b(i) > TH_{high}) = Q\left(\frac{TH_{high} - R_b(i)}{\sigma}\right)$$

Where $Q(\cdot)$ is the complementary distribution function of the standard Gaussian, i.e., $Q(x) = \int_x^\infty (1/\sqrt{2\pi})e^{-t^2/2} dt$, $R_a(i)$ and $R_b(i)$ indicate the RSSI values from AP_a and AP_b at slot i , and σ (in dB) expresses the standard deviation.

Radio channel model. The received signal strength is estimated by log-normal shadowing path-loss. According to this model, $R(i)$ (in dBm) (RSSI level at a given slot i) from the transmitter is given by [34]:

$$R(i)[dBm] = P_t[dBm] - \overline{PL}(d_0)[dB] - 10n\log_{10}(i/d_0) - X_\sigma[dB] \quad (1)$$

Where i corresponds to distance, P_t is the transmission power, $\overline{PL}(d_0)$ is the measured path-loss at reference distance d_0 , n is the path-loss exponent, and $X_\sigma = N(0, \sigma)$ is a normal variable (in dB). The term X_σ models the path-loss variation across all locations at distance i from the source due to shadowing, a term that encompasses signal strength variations due to the characteristics of the environment (i.e., occlusions, reflections, etc.).

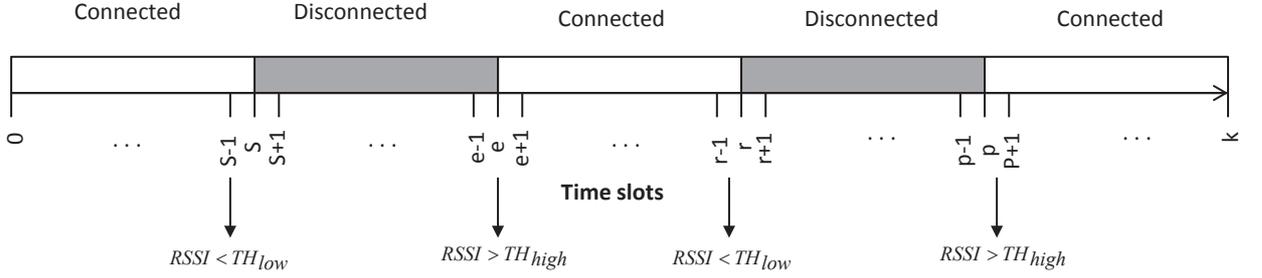


Fig. 9. The moments of detecting different events; at slot $s - 1$ the link quality level is below TH_{low} and starts a hand-off, at slot e is above TH_{high} and stops the hand-off, at slot $r - 1$ is again below TH_{low} , and at slot p is again above TH_{high} . The shadowed areas are the disconnected regions that the MN is performing the *Discovery Phase*.

Smart-HOP probabilistic model. To evaluate the performance metrics, we define the possibility of starting and ending a hand-off process at each slot. Figure 9 shows an example where the MN encounters disconnections and connections in different time slots. As explained earlier, in WSNs with hard hand-off, the MN communicates with a single AP at each time-slot. The MN is initially connected to AP_a —see Figure 8. When the MN is traveling from AP_a to AP_b , it tracks the likelihood of the RSSI going below a threshold level, TH_{low} , at each sampling interval. By observing a low quality link, the hand-off process starts. The probability of starting a hand-off at slot $s \in [1, k]$ is defined as follows (k indicates the total number of slots).

$$P(Start(s)) = \left[\prod_{i=1}^{s-1} P(R_a(i) \geq TH_{low}) \right] \times P(R_a(s) < TH_{low}) \quad (2)$$

The first part of the equation indicates the observation of a number of slots ($s - 1$) with good/acceptable link quality level (above TH_{low}). The second part denotes the observation of the low link quality for the first time (below TH_{low}). The following settings are used in all future evaluations across this section: $\sigma = 4$ dB, $\eta = 4$, $P_t = 0$ dBm, $d_0 = 1$ m, $d = 5$ m, $PL(d_0) = -55$ dB, $w_s = m = 1$, $TH_{low} = -90$ dBm and $TH_{high} = -85$ dBm. The network related values are set according to the most efficient scenario of the *preliminary experiments*.

By starting the hand-off process at slot/location s , the MN disconnects from the corresponding AP that was servicing the MN. At this moment, MN starts assessing the other neighboring APs to choose the one with higher threshold level ($RSSI > TH_{high}$). The hand-off finishes when the MN observes a high link quality. Equation 6 formulates the probability of ending a hand-off at slot e considering the fact that the hand-off would have been started at slot s and the MN was disconnected from either AP_a or AP_b .

$$P(End(e) | Start(s)) = \left[\prod_{i=s+1}^{e-1} (P(R_a(i) < TH_{high}) \times P(R_b(i) < TH_{high})) \right] \times [1 - (P(R_a(e) < TH_{high}) \times P(R_b(e) < TH_{high}))] \quad (3)$$

This equation assumes that the hand-off occurs at slot s . The ending moment at slot $e \in (s + 1, k]$ happens at a later stage by comparing the RSSI level of APs to a higher threshold level, TH_{high} . Hence, in practice it is a

conditional probability and depends on a situation that has taken place previously at slot s .

The time span between the starting slot and the ending slot is called hand-off delay. By considering each point as a starting moment of a hand-off process, we characterize the ending moments by the probabilities defined in Equation 6. The expected hand-off delay is computed by getting the weighted sum of all possible hand-off periods. It is defined as the product of the time spent in each possible hand-off process started at slot s and ended at slot e by the correspondent probabilities of starting a hand-off at slot s , $P(Start(s))$, and ending it at slot e , $P(End(e) | Start(s))$. For each hand-off starting at slot s , the hand-off would end at one of the slots from $s + 1$ to k . The sum of all these possible situations defines the expected delay for a hand-off started at a specific slot s . The overall expected hand-off delay is given by:

$$Delay(s, e) = \sum_{s=1}^{k-1} \left(\sum_{e=s+1}^k ((e - s) \times P(End(e) | Start(s)) \times P(Start(s))) \right) \quad (4)$$

In order to measure the ping-pong effect in smart-HOP, a new term is defined that is called probability of restarting a hand-off. This situation happens when a MN performs hand-off at an improper moment, thus leading to an unnecessary hand-off. The restarting of a hand-off always occurs after successfully ending the first hand-off at slot $r \in (2, k]$. This means that the probability of restarting is also a conditional probability that depends on ending a hand-off at an earlier stage. Since the MN may have been connected to either AP_a or AP_b , the signal strength should be evaluated for both cases. The equation is defined as follows.

$$P(Restart(r) | End(e)) = \left[\prod_{i=e+1}^{r-1} (1 - P(R_a(i) < TH_{low}) \times P(R_b(i) < TH_{low})) \right] \\ \times [P(R_a(r) < TH_{low}) \times P(R_b(r) < TH_{low})] \quad (5)$$

The second disconnection of the MN in this trip will be ended at slot p , which is given by.

$$P(Ping - pong(p) | Restart(r)) = \left[\prod_{i=r+1}^{p-1} (P(R_a(i) < TH_{high}) \times P(R_b(i) < TH_{high})) \right] \\ \times [1 - (P(R_a(p) < TH_{high}) \times P(R_b(p) < TH_{high}))] \quad (6)$$

To find out the probability of ping-pong effect, the full history of a MN since the first start of hand-off to the end and restarting again are taken into account. Equation 7 illustrates the cases that lead to a ping-pong effect at slot p as follows.

$$\begin{aligned}
P(\text{Ping-pong}(p)) = & \left[\left(\prod_{i=1}^{s-1} P(R_a(i) < TH_{low}) \right) \times P(R_a(s) < TH_{low}) \right] \times \\
& \left[\prod_{i=s+1}^{e-1} (P(R_a(i) < TH_{high}) \times P(R_b(i) < TH_{high})) \right] \times [1 - P(R_a(e) < TH_{high}) \times P(R_b(e) < TH_{high})] \times \\
& \left[\prod_{i=e+1}^{r-1} (1 - P(R_a(i) < TH_{low}) \times P(R_b(i) < TH_{low})) \right] \times [P(R_a(r) < TH_{low}) \times P(R_b(r) < TH_{low})] \times \\
& \left[\prod_{i=r+1}^{p-1} (P(R_a(i) < TH_{high}) \times P(R_b(i) < TH_{high})) \right] \times [1 - P(R_a(p) < TH_{high}) \times P(R_b(p) < TH_{high})] \quad (7)
\end{aligned}$$

To find out the total probability of ping-pong effect, we define the following equation in a more abstract way. For each case of hand-off occurrence at slot $s \in (0, k-2]$, there is a chance to finish the hand-off at one of the upcoming slots $e \in (s, k-1]$. Similarly for each e , as an ending slot, there is a chance of restarting another hand-off at slot $r \in (e, k]$.

$$\begin{aligned}
& \text{Total probability of ping-pong} = \\
& \sum_s^{k-3} \sum_e^{k-2} \sum_r^{k-1} \sum_p^k (P(S(s)) \times P(E(e) | S(s)) \times P(R(r) | E(e)) \times P(P(p) | R(r))) \quad (8)
\end{aligned}$$

Performance metrics. To evaluate the functionality of the smart-HOP mechanism, two main metrics are considered, which are derived from the above equations.

- 1) *probability of ping-pong effect.* It shows the probability of reconnecting to AP_a after the first hand-off from AP_a to AP_b . This situation happens after observing a low quality link $R_b(i) < TH_{low}$ at AP_b at slot i , where there was a high quality link $R_b(i-1) > TH_{low}$ at slot $i-1$.
- 2) *expected hand-off delay.* It indicates the expected hand-off delay for each possible starting point of hand-off from AP_a to AP_b .

In the following subsections, we study the impact of some parameters, which were either neglected or not feasible to address due to the network limitations in the *preliminary experiments*.

B. Impact of channel parameters

An increase in the path-loss exponent leads to longer hand-off delay and higher probability of ping-pong effect. The path-loss exponent varies depending on the environmental conditions. The path-loss parameter may be less dynamic in some applications with stationary nodes and static environments or oppositely may be highly variable in some other situations like mobile WSN applications [35]. Figure 10(a) illustrates the variation of the RSSI at AP_a while the MN is moving toward AP_b . The larger the path-loss exponent is, the higher the slope of the RSSI decrease will be. In smart-HOP design, we aim at choosing a hand-off starting level below the intersection of the received signal power from AP_a and AP_b . This will reduce the chance of ping-pong effect. The ending level

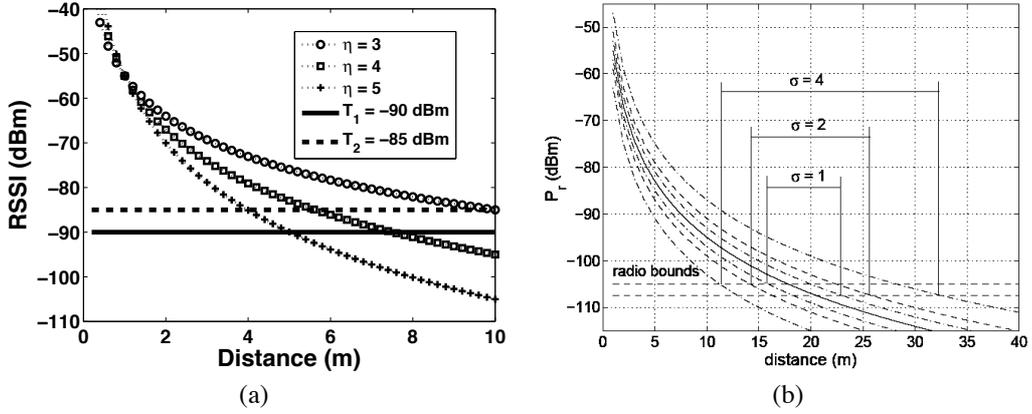


Fig. 10. Impact of channel parameters on the RSSI with $TH_{low}=-90$ dBm and $HM=5$ dBm, (a) impact of path-loss exponent on RSSI, and (b) impact of shadow fading on the RSSI [30].

Channel Parameters	$\eta=1$	$\eta=2$	$\eta=3$	$\eta=4$	$\eta=5$	$\eta=6$
$\sigma=1$	8.2e-099	1.4e-045	2.4e-014	0.0216	0.0387	0.0469
$\sigma=2$	3.1e-027	9.1e-014	2.5e-005	0.0324	0.0408	0.0470
$\sigma=3$	2.4e-013	2.8e-007	0.0022	0.0371	0.0422	0.0477
$\sigma=4$	2.6e-008	7.5e-005	0.0109	0.0398	0.0433	0.0496
$\sigma=5$	6.9e-006	0.0012	0.0215	0.0415	0.0443	0.0519
$\sigma=6$	1.6e-004	.0054	0.0297	0.0428	0.0453	0.0537

Fig. 11. Impact of channel parameters on the overall expected hand-off delay in seconds (sampling rate of every 50 ms).

is supposed to be at this intersection or slightly higher. In practice, it is recommended to pick a higher level for ending point to cancel out the immediate changes of the RSSI.

An increase in the shadowing variance enlarges the transitional region, which in turn causes higher link unreliability and ping-pong effect. This channel parameter describes the received signal strength fluctuation caused by flat fading. By increasing σ , the probability of entering the transitional region at closer distances from the transmitter and leaving it at farther distances increases; this results in a larger transitional region —see Figure 10(b) [30].

By enlarging the channel parameters, the hand-off delay increases. Figure 11 depicts a matrix, with the x-axis representing the path-loss exponent and the y-axis representing the shadow-fading. We observe an increasing trend in the hand-off delay in each row and column when increasing each channel parameter. A larger path-loss exponent causes faster RSSI decrease. Hence, the MN enters the hand-off process at earlier stages. Finding a high link quality is postponed to later stages, which in turn increases the hand-off delay. Larger shadow-fading increases the RSSI standard deviation, which expands the transitional region. Therefore, any disconnection from the point of attachment requires a longer time assessing the wireless link to detect a high quality link in the transitional region.

By enlarging the channel parameters, the probability of ping-pong effect increases. Figure 12 shows that increasing any channel parameter causes higher link variability, unreliability and instability. This is the main reason for noticing higher probability of ping-pong effect when increasing either the path-loss exponent or shadow fading parameters. Studying the channel parameters (σ, η) reveals the high dependency of the hand-off process on environmental

Channel Parameters	$\eta=1$	$\eta=2$	$\eta=3$	$\eta=4$	$\eta=5$	$\eta=6$
$\sigma=1$	0	0	1.8e-229	6.4e-144	5.4e-079	2.1e-034
$\sigma=2$	5.7e-120	3.7e-087	5.3e-060	1.7e-038	6.6e-022	2.2e-010
$\sigma=3$	1.0e-054	4.2e-040	5.7e-028	2.7e-018	1.0e-010	2.4e-005
$\sigma=4$	1.6e-031	2.7e-023	1.7e-016	6.8e-011	1.6e-006	0.0018
$\sigma=5$	1.4e-020	2.6e-015	5.5e-011	2.7e-007	1.7e-004	0.0128
$\sigma=6$	1.7e-014	7.2e-011	7.3e-008	2.8e-005	0.0022	0.0345

Fig. 12. Impact of channel parameters on the probability of ping-pong effect (sampling rate of 20 Hz).

TABLE II
CHANNEL PARAMETERS [30]

Environment	η	σ
Outdoor	4.7 (4.30-5.10)	4.6 (2.80-6.40)
Indoor	3.0 (2.67-3.23)	3.8 (2.60-5.00)

changes. However, these values do not fluctuate significantly in indoor environments. The variation of channel parameters for both indoor and outdoor environments is shown in Table II.

In an efficient hand-off algorithm, the MN should perform the process within at most a single sample (50 ms in this example). Figure 11 shows an acceptable amount of hand-off delay for most cases except with $\eta = 6$ and $\sigma > 4$. This condition rarely happens in outdoor environment (see Table II). Thus, we get to the conclusion that **smart-HOP is suitable for all environments, although for outdoor environments a user should perform a radio survey⁶ to obtain a better insight.**

C. Simulation model

We also performed a simulation study with MATLAB to verify the correctness of the probabilistic model [36]. In this model, we generated random values of RSSI at various distances from the serving AP and the neighboring AP with Equation 1. The mobile node started and ended the *Discovery Phase* by reading the RSSI values at each sampling slot. Studying the impact of network and channel parameters (TH_{low} , HM , m , η and σ), we observed similar results to the ones from the probabilistic model. In the simulation model, we are able to consider higher values of ws and m . These parameters were ignored in the probabilistic model, for simplicity. We assume that the MN is initially connected to AP_a . By considering a sliding window ws and low threshold level TH_{low} for starting a hand-off, the MN decides for the hand-off starting slot. Then by having the RSSI value of AP_b and considering the stability parameter m , the MN decides for ending the hand-off. This process repeats for 10,000 trips and the results are averaged at the end of the simulation.

Impact of link monitoring. The *link monitoring* is a parameter that is used in both the *Discovery Phase* and the *Data Transmission Phase*. In the preliminary experiments, we simply assumed $ws=3$ for both phases. In this

⁶It is difficult to predict the values of channel parameters during the experiment. A radio survey is a process that determines the channel values before performing an experiment.

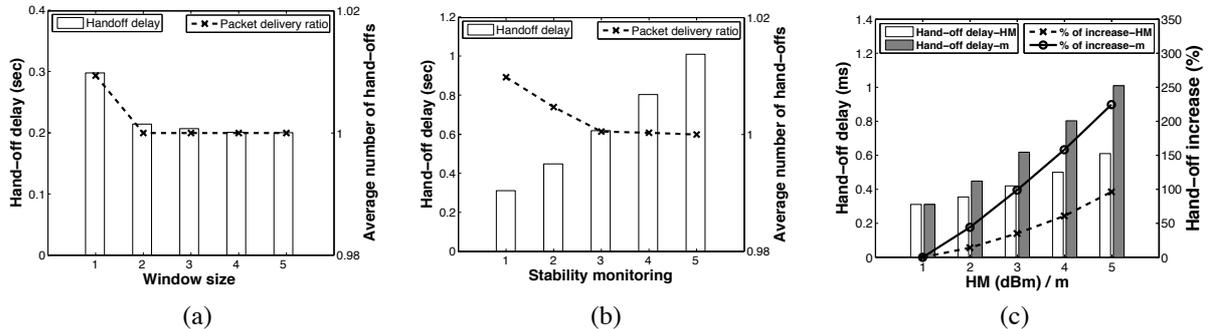


Fig. 13. (a) Impact of window size in the *Data Transmission Phase*, (b) Impact of *stability monitoring*, (c). compare *stability monitoring* (in simulation model) versus *hysteresis margin* (in analytical model).

simulation, we study the impact of *link monitoring* in each phase separately.

- 1) *Impact of link monitoring in the Data Transmission Phase*. By setting the $ws=3$ for the *Discovery Phase* and varying it from 1 to 5 in the *Data Transmission Phase*, we get a decreasing trend of hand-off delay for the first 3 cases and then it remains unchanged —see Figure 13(a). This happens to the number of hand-offs as well. This means that a small *link monitoring* value during the normal data communication of the MN, reduces the hand-off delay and the number of unnecessary hand-offs.
- 2) *Impact of link monitoring in the Discovery Phase*. Increasing the number of beacons for assessing the neighboring APs requires more time, which is proportional to the sampling frequency. This case is somehow similar to the stability parameter that increases the period of link assessment. It is apparent that considering a few samples can compensate the fluctuations of random RSSI values. Hence, it is not logical to assume a large *link monitoring* value for the *Discovery Phase* due to its negative impact on the hand-off delay. In the current model with 2 APs, the result is similar to the case when changing the stability parameter, thus it is not shown here. In case of higher density scenarios the results are different, but still the trend is equal.

Impact of stability monitoring. Increasing the *stability monitoring* reduces the link variability. Each unit of *stability monitoring* adds a new *Discovery Phase*, which is composed of a set of beacons and reply packets. The results in Figure 13(b) indicate that the hand-off delay has an increasing trend with a high slope, which is more steep than the case of increasing *link monitoring* during the *Discovery Phase*. Considering the ping-pong effect, there is an improvement with a small stability parameter. In practice, we can substitute the stability parameter with the *link monitoring* of the *Discovery Phase*. By this action, we can (i) reduce the link variability to eliminate the ping-pong effect and (ii) compensate the RSSI fluctuations to take accurate hand-off decisions.

Comparing correlated parameters. It is obvious that either enlarging the HM or increasing the *stability monitoring* reduces the link variability. It is interesting to compare the impact of these parameters before tuning them for the experimental tests. It is difficult to pick a special moment for starting a hand-off. According to the simulation model, we have a hand-off delay of 0.311 s with $m=1$ and $ws = 3$. The sampling rates of beacon and data period are set to 100 ms. This hand-off delay occurs at a 3.42 m distance from AP_a in the probabilistic model when $HM=1$ dBm. By increasing the stability parameter in the simulation model and *hysteresis margin*

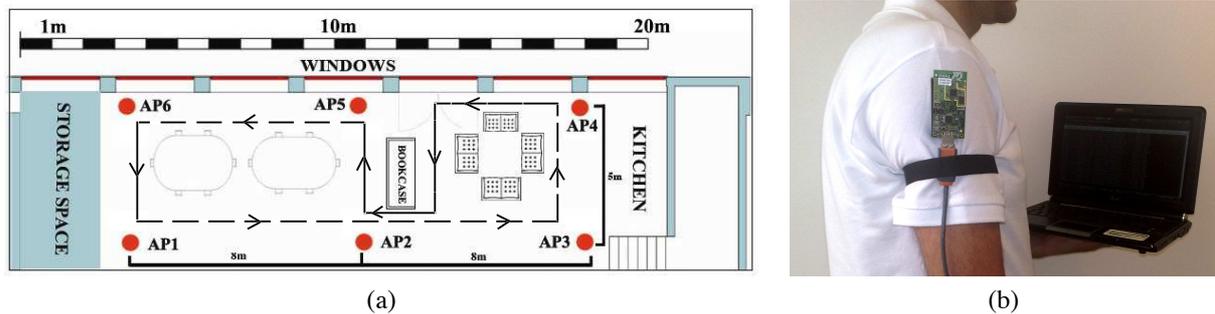


Fig. 14. (a) The APs' deployment in a large room, and (b) the MN attached to the body.

in the probabilistic model, we compare the hand-off delays at the same point of assessment, 3.42 m. The results indicate that the hand-off delay increases more severely by adding the stability parameter rather than by adding the *hysteresis margin*—see Figure 13(c). This shows its severe impact on the delay that should be taken into account when designing a hand-off mechanism.

Lessons learned from the simulation model.

- 1) *link monitoring* in the *Data Transmission Phase* does not have a significant impact on the overall performance. Setting small number of *ws* is enough to reduce the hand-off delay.
- 2) Tuning the *stability monitoring* parameter enables to eliminate the ping-pong effect, but large values increase the hand-off delay remarkably. It is recommended to either choose a small value of *stability monitoring* or *link monitoring* during the *Discovery Phase*.
- 3) The *stability monitoring* can compensate the link variability much more significantly than the *hysteresis margin*, at the cost of a higher hand-off delay.

V. EXPERIMENTAL EVALUATION

The *preliminary experiments* [13] revealed the best thresholds for a hand-off process in a controlled environment. The probabilistic analysis proved that, in theory, smart-HOP is able to perform efficient hand-offs. At this stage, we set further experiments to enable a deeper analysis and fine-tuning of the algorithm in a more realistic environment. We deployed a maximum of 6 APs with a minimum power level of -25 dBm in a 80 m^2 room. The APs were attached to walls at 1.5 m height from the ground (to guarantee a better connectivity). Figure 14(a) illustrates the position of each AP, furniture, walls and windows. Figure 14(b) shows the mobile node attached to the body and the logging PC⁷.

As we mentioned earlier, the two parameters of low threshold level and the respective *hysteresis margin* are very important. Instead of starting the experiment with all the 6 APs, we first confine the scenario to 2 APs (AP_1 and AP_2 in Figure 14(a)) and attached the MN to the body of a person. The sensor is attached to the shoulder,

⁷At the beginning, we connected all APs to one laptop with passive USB cables and USB2.0 hubs. Then we observed some data loss during data transfer through the UART port. Adding more PCs did not solve the problem completely. Hence, we managed to get the data log from the MN with the cost of a person carrying a laptop during the experiment.

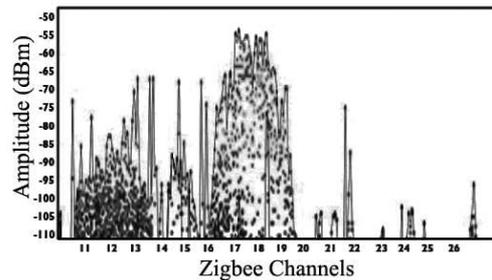


Fig. 15. Channels activity before the experiment.

which faces the anchors in each trip from AP_1 to AP_2 and, on the way back, the body eliminates the Line-of-Sight (LoS) communication. We refer to this set of tests as *baseline experiments*. Less APs guarantees that there is no overlapping between the neighboring APs. The person walks 4 times between these APs with a normal human walking speed (about 1 m/s).

The experimental area is a lab with at most 10 people sitting and three to five people moving randomly in all locations. The tests were performed on channel 15 of the CC2420 radio, which maybe affected by different sources of interference in the 2.4 GHz band such as WiFi devices, Bluetooth and microwave ovens. In order to obtain a better understanding of the frequency activities, we measured the 2.4 GHz spectrum usage; a WiFi-Spy spectrum analyzer verified that there was very low interference from other RF sources —see Figure 15.

A. Evaluation methodology

We evaluate smart-HOP in this realistic environment in two steps; (i) *baseline experiments* using 2 APs, to further analyze the lower threshold level and the *hysteresis margin* and (ii) *extended experiments* using 6 APs, to study the impact of *stability monitoring* and *link monitoring*. In all tests, we employ SNR-based smart-HOP as it encompasses the interference in the environment.

Baseline experiments. In the *preliminary experiments* (see Section III), we considered four groups of lower threshold level (-95, -90, -85 and -80 dBm) with 2 values of *hysteresis margin* 1 and 5 dBm. The results indicated that -95 dBm is not a choice as the MN enters in the disconnected region. Now, we consider a wider range of lower threshold levels [-76, -90 dBm] increasing in 2 dBm steps, and higher threshold levels in the range of [-75,-89 dBm], which in turn generate *hysteresis margins* of 1 to 15 dBm. All the 8 cases of lower threshold levels with variations of HM lead to 36 combinations. We compare all these situations in terms of number of hand-offs, hand-off delay and packet delivery ratio in walking four times between APs (AP_a and AP_b). The main goal at this stage is to pick situations that are more likely to be efficient and then reassess them with 6 APs, for further comparison. We depict the performance of smart-HOP in terms of number of hand-offs, average hand-off delay and absolute packet delivery ratio in Figures 16, 17 and 18. We observe the following facts.

- 1) Selecting the lower threshold level from the lower end of transitional region with a wider *hysteresis margin* eliminates ping-pong effect —looking at Figure 16. Except cases (7) and (8) with small threshold levels and

TABLE III
DESCRIPTION OF CASES CONSIDERED IN BASELINE EXPERIMENTS

Cases	TH_{high}	TH_{low}	HM
Case1	-75 dBm	-76, -78, -80, -82, -84, -86, -88, -90 dBm	1-15 dBm
Case2	-77 dBm	-78, -80, -82, -84, -86, -88, -90 dBm	1-13 dBm
Case3	-79 dBm	-80, -82, -84, -86, -88, -90 dBm	1-11 dBm
Case4	-81 dBm	-82, -84, -86, -88, -90 dBm	1-9 dBm
Case5	-83 dBm	-84, -86, -88, -90 dBm	1-7 dBm
Case6	-85 dBm	-86, -88, -90 dBm	1-5 dBm
Case7	-87 dBm	-88, -90 dBm	1-3 dBm
Case8	-89 dBm	-90 dBm	1 dBm

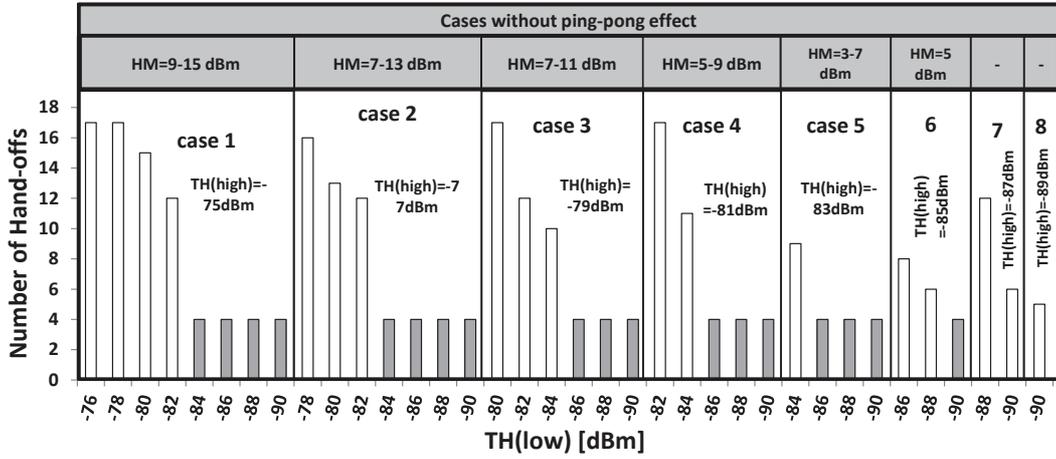


Fig. 16. Total number of hand-offs in baseline experiments.

narrow *hysteresis margin*, we observe acceptable situations (shadowed bars) in other cases, corresponding to four hand-offs (the minimum for that trip).

- 2) Either very wide *hysteresis margin* or narrow margin with large threshold level causes huge hand-off delay. A wide *hysteresis margin* obliges the MN to stay at the *Discovery Phase* for longer periods of time. A narrow *hysteresis margin* with large value of lower threshold level causes an excessive number of hand-offs that eventually enlarges the hand-off delay. In theory, an efficient hand-off process (which performs fast and without ping-pong effect) should perform within one sample. For instance, if the sampling is every 100 ms, the hand-off delay should be 100 ms in an efficient hand-off process. This value is depicted by a horizontal line in Figure 17 to have a reference in finding the acceptable scenarios. Results indicate that selecting $TH_{high} > -83$ dBm leads to higher hand-off delays.
- 3) A lower hand-off delay causes higher packet delivery ratio. Observing the results of packet delivery ratio in Figure 18, we can make two observations; (i) increasing the *hysteresis margin* in all cases reduces the link variability and increases the packet delivery ratio, and (ii) higher values of packet delivery are achieved in situations with lower hand-off delay. The more efficient scenarios are noticed with HM between 3 and 7

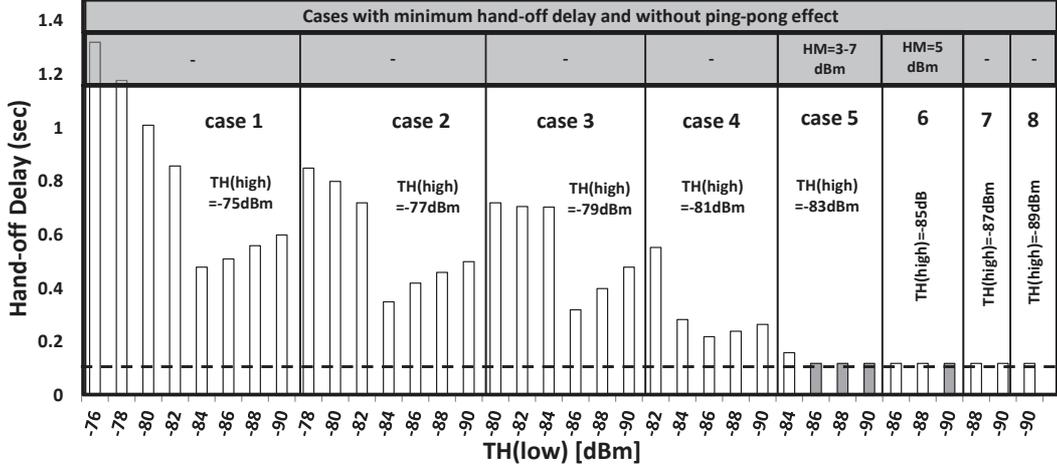


Fig. 17. Average hand-off delay in baseline experiments. The horizontal line presents the minimum achievable hand-off delay obtained by analytical model.

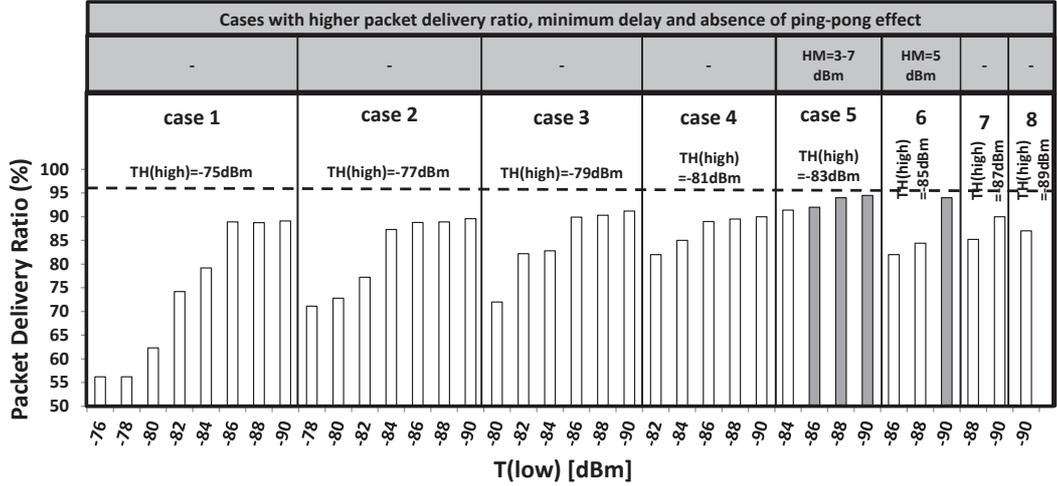


Fig. 18. Absolute packet delivery ratio in baseline experiments. The horizontal line presents the packet delivery ratio of a simple broadcast scenario (MN broadcasts instead of performing smart-HOP).

dBm and low threshold level in the range of -86 to -90 dBm.

The efficient scenarios in the *baseline experiments* (the intersection of efficient scenarios), are more elaborated in the *extended experiments*. The *baseline experiments* reveal that with the smallest TH_{low} (-90 dBm) and $HM=5-7$ dBm, the hand-off delay is minimum, while obtaining a maximum delivery of packets. An educated solution is to keep the MN connected to the current link as much as possible, similarly to the *preliminary experiments*. Thus, we keep the same threshold level for starting the hand-off ($TH_{low}=-90$ dBm) and compare the results of various HMs (3 to 8 dBm).

Extended experiments. To find the best setting for the *hysteresis margin*, we increase the number of APs to six. Adding more APs creates a more realistic environment in which the mobile node experiences links overlapping. For each set of experiments according to the selected *hysteresis margin*, the person walks in the room while the mobile node sends data periodically (every 100 ms). The person starts walking from AP_1 along the dashed line shown

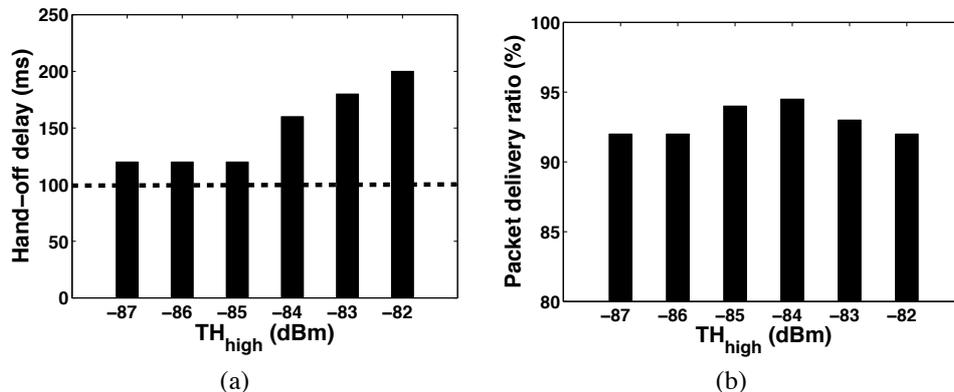


Fig. 19. More extensive experimental evaluation with 6 APs by considering $TH_{low}=-90$ dBm, (a) average hand-off delay. The horizontal line shows the optimum hand-off delay computed by the analytical model. (b) absolute packet delivery ratio.

in Figure 14(a). In some parts of the way, there are obstacles that prevent Line of Sight (LoS) communication. Moreover, random movement of people creates more dynamics in the environment. For each set of experiments, the person walked for about 15 minutes (transmitting 10,000 packets), which is about 15 full laps (dashed line circuit). At the end, we compared the average hand-off delay and the packet delivery ratio.

Increasing the *hysteresis margin* enlarges the hand-off delay as it forces the MN to attach to a higher link quality AP. Figure 19(a) shows that the hand-off delay is minimum with 3-5 dBm *hysteresis margin* and then it records a gradual increase. The reason is that by enlarging the margin, the chance of staying in the *Discovery Phase* for more than one period is higher. The one period stands for the case where after sending a burst of beacons and receiving reply packets, the MN is able to observe a good link to make the hand-off. The packet delivery ratio in Figure 19(b) illustrates a higher packet delivery ratio with $HM=5$ and 6 dBm. The packet delivery decreases with HM since there are unnecessary hand-offs. The higher HM causes fewer packets delivered as the MN stays in the *Discovery Phase* longer.

The *hysteresis margin* should be tuned to achieve an optimal trade-off between the delivery rate and delay. By choosing the lower end of the transitional region (-90 dBm) as the threshold level, the *hysteresis margin* of 5 dBm is the best choice. The *stability monitoring* and the *link monitoring* parameters are the two other important parameters, which are studied in these experiments.

Increasing the *stability monitoring* increases the hand-off delay. Increasing the *stability monitoring* has a direct impact on the hand-off delay. Adding one unit to the stability requires observing a high quality link for one more sliding window. It is interesting to notice that this raise does not have a good impact on the packet delivery since we are shrinking the *Data Transmission Phase*. Considering the fact that a slight change in stability increases the hand-off delay significantly, it is wise to tune other related parameters with less impact. Thus, we opt for choosing the minimum stability value for the experiment and play with other network parameters.

The window size parameter compensates the dynamics of the link. It defines the *link monitoring* parameter in the hand-off process, which should neither be too small nor too large. This parameter compensates the link variability and sudden RSSI changes. In a controlled environment, $ws=3$ was selected, according to the suggestions

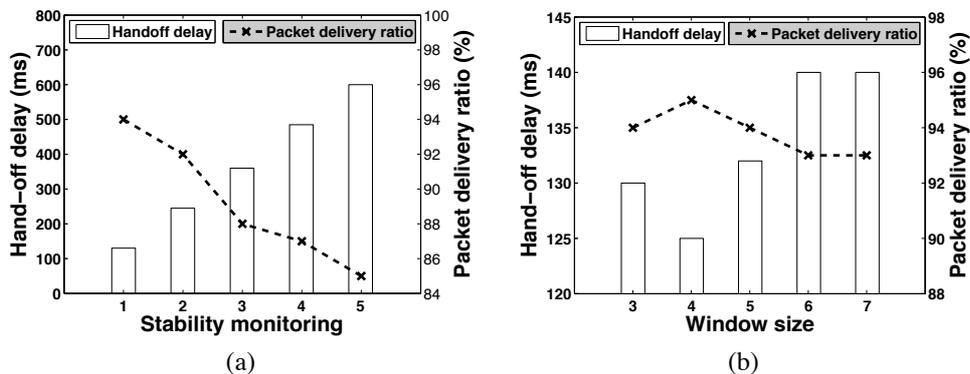


Fig. 20. (a) Impact of stability monitoring, (b) impact of link monitoring.

from related work. However, in a realistic scenario, there are more sources of disturbance: (i) there is a natural variation in human gait. When a movement experiment is repeated, a person carrying a node may move a bit faster or slower than before, or may deviate slightly from the previous path. Hence, a node may detect different signal strength at the same position [37]. (ii) The human body partly absorbs electromagnetic radiation, and the amount of absorbed energy depends –among other things– on the person’s physique and pose, and the radio frequency [38]. The results indicate that in a real environment a slightly higher window size, $ws=4$, increases the accuracy. But enlarging more than this value does not improve the performance since it provides coarse grain information of the link. Considering wider window sizes reduces the responsiveness of the hand-off process.

VI. BACKGROUND AND RELATED WORK

Hand-off mechanisms have been widely studied in Cellular [14]–[16] and WLANs [17], [18], [39], but did not receive the same level of attention in low-power wireless networks. In cellular networks, the hand-off decision is centralized and typically coordinated by a powerful base-station, which is able to gather considerable information about the network topology and mobile node proximity [14]. Cellular networks also take advantage of sophisticated CDMA radios to perform soft hand-off techniques [40]. The major challenge in cellular networks is the *call dropping* effect during an ongoing call, while switching between base stations [41]. A similar problem occurs due to the lack of available channels (so-called *call blocking*). In [16], some channels are exclusively allocated to hand-off calls, also known as *guard channels*. In [15], a queuing strategy has been applied to delay the hand-off 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 [39]. While Cellular systems require a continuous monitoring of the radio signal level, WiFi-based systems monitor the signals only after service degradation. The main concern of 802.11 hand-off protocols is to minimize the hand-off latency. A hand-off process in WiFi-based systems is divided into the Discovery and Re-authentication phases. The channel scanning during a *Discovery Phase* is the most time consuming process. The authors in [42] propose a data link layer with fast hand-off, which uses selective scanning

and records the scan results in the AP's cache. When a MN moves to a location visited before, it pings the nearby APs for their available channels. In [18], each AP records the neighboring AP's information in a *neighbor graph* data structure. Then the AP can inform the MNs about which channels have neighboring APs. The MN needs to scan only those channels.

The key difference between WiFi and WSN hand-offs is that in WiFi multiple radios are used to reduce the hand-off latency, while in WSNs a single radio is used. In WSN, a centralized hand-off approach is not feasible as it incurs in a high overhead. Hand-offs in sensor networks should be distributed –similarly 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. As previously described, there are two major strategies for the hand-off process: soft hand-off (network layer) and hard hand-off (MAC layer). The soft hand-off requires lots of packet exchanges, thus impacting the sustainability of energy-constrained nodes. In any case, we address some of the latest algorithms using soft hand-off in WSNs [43], [44]. In [43], the authors focus on the hand-off in networks with mobile sensors and gateways. The mobile node is supposed to be in the range of multiple gateways that are periodically broadcasting router advertisement (RA) packets. Advertising their presence, enables the mobile node to decide for the best gateway. The connectivity of the network relies on the RA packets frequency; high frequency leads to network congestion while low frequency leads to low responsiveness of the network (thus to longer network inaccessibility).

A soft hand-off within 6LowPAN is proposed in [44]. The paper claims zero hand-off time and zero packet losses. The process is similar to [43]. However, it takes advantage of using two additional control messages, namely *Join* and *Join Ack* that are sent/received when the MN is still attached to the serving AP. This algorithm requires a huge amount of control message exchanges, increasing the probability of network congestion. Moreover, the zero hand-off delay was observed in a low sampling rate scenario, which is not the case in many applications.

A more reasonable approach for low-power wireless networks (hard hand-off) is based on data link layer solutions [9], [13]. The respective authors claim that their approaches are adequate for passive decision with non-real-time support in [9] or for active decision with real-time support in [13]. In [9], the authors describe a wireless clinical monitoring system collecting vital signs from patients. In this study, the mobile node connects to a fixed AP by listening to beacons periodically broadcast 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 (similar to soft hand-offs) and hand-offs are passively performed whenever the mobile node cannot deliver data packets.

We proposed a more reliable and faster hard hand-off approach for WSNs [13]. In this algorithm, hand-off is initiated at the mobile node, opposed to other algorithms in the literature. The MN keeps track of the link quality level during the *Data Transmission Phase*. A timer is responsible to detect the unreachability of the serving AP. Hence, the user is able to detect the link degradation and unreachability of the serving AP within a short time. Then, the MN spends a time window assessing the neighboring APs to change the point of attachment.

The link quality is one of the parameters that significantly affects the hand-off performance. 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 [45], [46]. In our case, due to the dynamics imposed by mobility, we use a simple and fast sampling of RSSI and SNR, which have been shown to provide reliable metrics [22], [47].

VII. CONCLUDING REMARKS

To the best of our knowledge, we are the first to systematically and empirically evaluate the hand-off in low-power networks. We believe that this is important, because a panoply of WSN applications may require mobile nodes to report information reliably and in real-time, such as in clinical monitoring and industrial automation. We proposed a reliable hand-off procedure that we dubbed as smart-HOP [13]. This hand-off scheme enables the MN to deliver data through the neighboring AP that offers the best link quality. In this line, some key parameters have a more significant impact on the performance of the hand-off. The results in a controlled environment revealed the best threshold level ($TH_{low}=-90$ dBm), *hysteresis margin* ($HM=5$ dBm) and *stability monitoring* ($m=1$) values, achieving hand-off delays of few tens of milliseconds and relative packet delivery ratio of around 98%.

It is well known that the performance of a low-power system is prone to the environmental conditions. Thus, we conceived a probabilistic model to investigate the impact of the most relevant channel parameters on the hand-off process. We showed that the environmental changes have a direct impact on the smart-HOP performance, but it ends up performing well in various channel conditions. To have a better knowledge of the smart-HOP performance, it is recommended to perform a radio survey (to determine the path-loss exponent and shadowing standard deviation values) before the experiment. A simulation model was also designed to verify the probabilistic model. We studied the impact of network and channel parameters, confirming the correctness of the probabilistic analysis. The impact of *link monitoring* and the *stability monitoring* parameters were also investigated. It was revealed that the *stability monitoring* has much more strength than the *hysteresis margin* in what concerns the hand-off delay.

We performed an extensive set of experiments in a more realistic environment. These were performed in a large room with more people around, while the MN was attached to the shoulder of a person and access points (two to six) were attached to walls. A wider range of parameters was considered for the performance analysis (TH_{low} from -90 to -76 dB, HM from 1 to 15 dBm, m from 1 to 5 and ws from 3 to 7). We obtained similar parameter settings as in the initial tests, which confirmed the stability of the smart-HOP mechanism in various environmental conditions and for several network scenarios.

The smart-HOP design shows some advantages but also limitations. It enables fast and reliable mobility support in low-power networks. It requires a number of stationary APs that are deployed in such a way to provide minimum overlap. In a dense deployment, the MN is always in the connected region of one AP, which rarely happens in WSN applications. smart-HOP is inefficient for dense deployments as it is tuned based on the concept of existing transitional regions. Moreover, the single radio characteristic limits the number of MNs that can be serviced at each AP. In cellular networks, each base station supports hundreds of MNs. The 802.15.4 radio allows one communication at each instance of time that limits the number of MNs.

This paper described the design and implementation of smart-HOP in a “protocol-agnostic way” with one MN and a number of APs. A future direction of this work is to support the smart-HOP within standard and commercial

off-the-shelf technologies (e.g. 6LoWPAN).

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