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Using SmartMesh IP in Smart Agriculture and Smart Building Applications

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Abstract

We deploy two low-power wireless networks, one in a Smart Agriculture setting (a peach orchard), one in a Smart Building. Both networks use out-of-the-box SmartMesh IP technology to gather sensor values, as well as extensive network statistics. This article presents an in-depth analysis of the performance of both networks, and compares them. Nodes in both exhibit end-to-end reliability of 100%, with an expected lifetime between 4 and 8 years. We show how – contrary to popular belief – wireless links are symmetrical. Thanks to the use of Time Slotted Channel Hopping (TSCH), the network topology is stable, with at most 15 link changes on average per day in the network. We conclude that TSCH as implemented by SmartMesh IP is a perfectly suitable IoT solution for Smart Agriculture and Smart Building applications.

1 Introduction

Peaches do not like frost. If during the blooming season (September in Argentina), temperature gets below $-3°C$ for only a couple of hours, the flowers freeze, and no peaches are produced. In 2013, 85% of the peach production in the Mendoza region (Western Argentina) was lost because of frost events. Farmers can lose everything in only a couple of hours. Yet, if they are warned

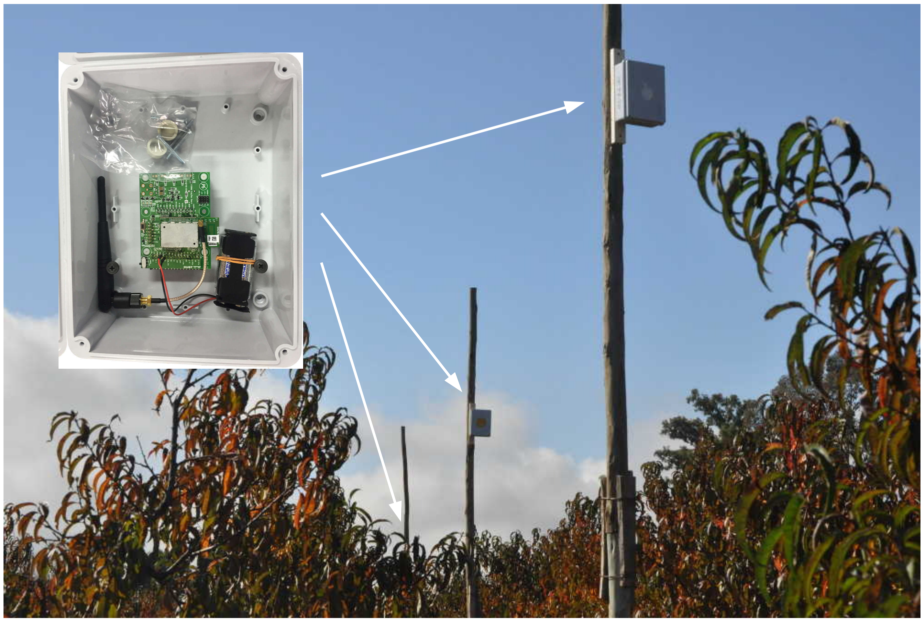


Figure 1: Devices deployed in a peach orchard near Mendoza, Argentina, for the Smart Agriculture use case.

of a frost event a couple of hours ahead, they can install heaters throughout the orchard, and use big fans to move the hot air around. Fighting the frost event is not the challenge, what is hard is predicting them.

The goal of the Smart Agriculture deployment (part of the PEACH [1] project) is to predict frost events in a peach orchard. We install sensors around the orchard that measure air temperature, air relative humidity, soil moisture and soil temperature. We feed the collected data into a database, and by analyzing the data in real-time we can identify patterns in the data to predict frost events.

Because of the heavy machinery that moves inside the orchard, using cables to interconnect the sensors is not an option. The main challenge is to deploy a system that provides both high end-to-end reliability and long lifetime, without using cables. We use SmartMesh IP off-the-shelf, the low-power wireless mesh solution from Analog Devices. The sensor devices are battery-powered and equipped with a radio. They form a multi-hop mesh topology, and collaborate to route the data generated by the devices (called “motes”) to a gateway. This gateway is connected to the Internet, and forwards the gathered data to the servers in Paris, France. Data appears on the web interface of the servers seconds after it was gathered by the sensor network.

The Smart Agriculture network is deployed in a peach orchard of 206 trees, planted in a 50 m × 110 m area (shown in Fig. 3a). The low-power wireless network is composed of 18 sensor motes uniformly distributed between the peach

(a) outdoors (b) indoors

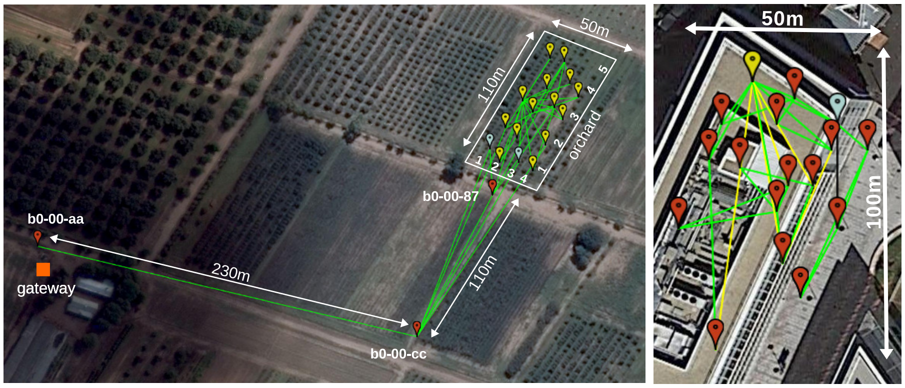
Figure 2: Devices deployed in the Inria-Paris offices for the Smart Building use case.

trees, and 3 relay motes which connect the orchard to an Internet-connected gateway some 300 m away. Each mote is placed in a water-tight box that is fixed on a 4 m high pole (see Fig. 1).

To complement and compare the network performance gathered from the Smart Agriculture deployment, we deploy a second Smart Building low-power wireless network in an office building in Paris, France. 14 motes are placed on the ceiling of one floor of the building, 3 additional motes are placed outside the building, on lamp posts (Fig. 3b). The 14 motes inside are fixed to the ceiling using magnets; the 3 motes outside are placed in a water-tight boxes (Fig. 2). Thanks to the "peel-and-stick" nature of this low-power wireless technology, deployment takes less than an hour.

In the Smart Agriculture deployment, we use four types of SmartMesh IP devices. Inside the orchard, 2 DC9018 boards feature an external antenna, 16 DC9003 boards have a chip antenna. We deploy 3 long-range repeaters outside the orchards to connect the network to the Internet-enabled gateway, located some 300 m away. In the Smart Building deployment, we use 2 types of SmartMesh IP devices: 11 DC9003 boards (chip antenna), 1 DC9018 board (external antenna). For both deployments, the gateway is composed of a Raspberry Pi single-board computer connected to a DC2274 SmartMesh IP manager over USB. All boards are off-the-shelf, manufactured by Analog Devices.

The goal of this article is to analyze the network statistics over each of



(a) Smart Agriculture (b) Smart Building

Figure 3: Aerial view of the topology of both deployments. The deployment is done in both cases in roughly a 50 m × 100 m area.

the 3-month periods, precisely assess the performance of both networks, and contrast/compare them. This article makes the following contributions:

- We confirm that the TSCH technology as implemented by SmartMesh IP exhibits years of battery lifetime and wire-like reliability in all cases;
- We show that channel hopping causes the network topology to be very stable, with at most 15 link changes on average per day on the 14-node and 18-node networks;
- Contrary to popular belief, we show that links in the networks are symmetrical, i.e. they exhibit the same signal strength in both directions of the same link;
- We conclude that TSCH as implemented by SmartMesh IP is a perfectly suitable IoT solution for Smart Agriculture and Smart Building applications.

This article in an extension of a previously published paper [2], which presents results for the Smart Agriculture deployment, over a 3-week period. This article extends this work and offers analysis over a 3-month period, and contrasts and compares the performance of SmartMesh IP in the Smart Agriculture deployment with that in a (new) Smart Building deployment.

The remainder of this article is organized as follows. Section 2 lists the related work on real-world deployments. Section 3 gives details about TSCH and explains why we chose SmartMesh IP Section 4 describes the types of network statistics, and the dataset of statistics collected over each 3 month period. Section 5 presents results that confirm assumptions about what we can expect for a real-world TSCH SmartMesh IP deployment. Section 6 presents not so intuitive results about link symmetry and network stability. Finally, Section 7 concludes this article and discusses further improvements.

2 Related Work

Previous work on Smart Agriculture has shown the importance of low-power wireless technologies [3]. The less current the motes draw, the longer the network operates without changing batteries. Wire-like network reliability is important in Smart Agriculture applications, as the data feeds productivity decision processes and triggers actions in real time. One example is frost prediction, as the analysis of sensor data triggers a warning that goes to the farmer about the imminence of a frost event. Loosing data is not an option. The key requirements for a Smart Agriculture application is low maintenance, energy-efficiency, reliability and ease of operation.

Smart buildings save energy by automating controls and optimizing systems. This adds value to leasing and sales of properties [4]. Smart Building applications face external interference, as the low-power wireless mesh networks are co-located with other technologies sharing the same frequency bands. For example, SmartMesh IP operates in the same 2.4 GHz band as WiFi and Bluetooth. On top of the requirements for Smart Agriculture applications, a solution deployed in a building must be resilient to external interference.

Deploying IoT-based solutions in real-world application is complex, and involves elements well beyond the low-power wireless network. Barrenetxea et al. [5] survey experimental studies and discuss best practices from system conception to data analysis.

The Smart Agriculture and Smart Building deployments described in this article use IEEE802.15.4 technology. In the 2015 amendment of IEEE802.15.4 [6], the IEEE has introduced enhancements to the medium access control sub-layer of the standard. The major enhancement is Time Synchronized Channel Hopping (TSCH), a technique which increases the reliability and lowers the power consumption of networks [7]. While TSCH was designed for industrial applications, this article shows that it operates equally well in the Smart Agriculture context. Section 3 provides an overview of TSCH technology, and delves into SmartMesh IP, the market-leading commercial implementation.

3 Time Synchronized Channel Hopping and SmartMesh IP

The TSCH mode was added to the IEEE802.15.4 standard in its 2015 revision. This mode inherits from several generations of industrial standards, and make IEEE802.15.4 ready for the Industrial Internet of Things. This section surveys TSCH and how it integrates into IEEE802.15.4, and describes SmartMesh IP, today's market-leading TSCH-based product.

In a TSCH network, all devices are synchronized, and time is cut into timeslots. All communication is orchestrated by a schedule, which indicates to each node what to do in each of the timeslots: transmit, listen or sleep. The result is that the devices sleep most of the time (i.e $< 1\%$ duty cycle is common), which results in long battery lifetimes. On top of this mechanism, nodes "channel hop". That is, when node A sends multiple frames to node B, each frame is transmitted on a different frequency, according to a pseuso-random hopping sequence. The result is that, if one frame isn't transmitted successfully (node A does not receive a link-layer acknowledgment from node B), node A retransmits *on a different frequency*, thereby exploiting frequency diversity. Channel hopping (which Bluetooth and some cellular networks also exploits), is very good and combating multipath fading and external interference, the two main causes for a loss of end-to-end network reliability [8]. In a nutshell, time synchronization yields ultra low-power operation, and channel hopping yields ultra high reliability.

TSCH was introduced in low-power wireless industrial standards WirelessHART (2008) and ISA100.11a (2009). These standards have been very successfully rolled out in the industrial market (industrial process monitoring, factory automation). The new TSCH mode was added to the IEEE802.15.4 standard by the IEEE802.15.4e Task Group, to "better support the industrial markets". From a packet format point of view, this meant adding Information Elements, generic containers to carry TSCH-specific information, for example, the hopping sequence added to beacon frames.

SmartMesh IP is a commercial implementation of TSCH by Analog Devices [9]. The SmartMesh IP network stack combines the industrial performance of IEEE802.15.4 TSCH with the ease of use of 6LoWPAN, and is fully compliant to these standards. A SmartMesh IP network exhibits over 99.999% end-to-end reliability[8], and a SmartMesh IP node (even when routing) consumes less than 50 μA average current, resulting in over a decade of battery lifetime [10]. The security solution of SmartMesh IP is NIST-certified. It features secure Over-The-Air Programming (OTAP) out of the box, so it is possible to remotely update the firmware running on devices that are already deployed. It is designed to operate in the $-40°$C to $+85°$C industrial temperature range. With over 60,000 networks deployed around the world, and its market leader position, SmartMesh IP is a proven technology. We use SmartMesh IP at the core of the deployments presented in this article.

We integrate SmartMesh IP into our Smart Agriculture and Smart Building software solutions in two ways. On the embedded low-power wireless motes, we use the SmartMesh IP Software Development Kit (SDK) to create applications which sample the sensors attached every 30 s, and send the measurements into the Internet. On the gateway side, we develop software to gather the network statistics automatically generated by the motes every 5 min, and provide network health monitoring tools. After 3 months of operation, each deployment has produced 4 million temperature values and over 350,000 network statistics. This data is analysed and the main lessons learnt are presented in Sections 5 and 6.

type	Smart Agriculture	Smart Building
`mote_create`	133	85
`path_create`	4,098	1,403
`path_delete`	3,653	1,325
`HR_DEVICE`	132,758	154,698
`HR_DISCOVERED`	87,737	152,641
`HR_NEIGHBORS`	140,897	128,072

Table 1: The number of statistics collected over the 3 month period.

4 Statistics Collected

The Smart Agriculture network is deployed in a peach orchard in Junín, 45 km South-East of Mendoza in Western Argentina. No other electronic devices are present in the field. Farmers work inside the field with heavy machinery for 1-2 h every 20 days approximately. In the region, air temperature ranges between -9°C in winter (May-October) and 38°C in summer (November-April). Because of the sunny weather, day/night temperature swings of 10°C are not uncommon in winter.

The Smart Building network is deployed in the Inria-Paris offices (a research institute) in Paris, France. It is deployed in a typical 5-story office building, in which light-material walls separate offices which are arranged around a concrete core which houses the elevators. Several wireless technologies operate in the same building, including WiFi, Bluetooth and other IEEE802.15.4-based networks. Around 200 people work in that building, with lots of movement and activity during business hours.

Each device in the network produces both sensor data and network statistics. Network statistics can be separated in Events and Health Reports messages. *Event* messages are non-periodic notifications the network generates when a network event happens (e.g. a mote joins/leaves the network, a link is created/deleted). *Health Report* (HR) messages are sent periodically by each mote; they contain counters and statistics about that mote. HRs are used to assess the health and performance of the network.

Table 1 summarizes the number of events and HRs gathered during the 3 month periods of both deployments:

- `mote_create`. Each node in a SmartMesh IP network periodically sends beacons to announce the presence of the network. When a mote wants to join a network, it listens for those beacons. Once it has heard a beacon, the new mote starts a security handshake with the network. During that handshake, the SmartMesh IP manager sends a `mote_create` event notification over its serial port [11]. This is the event we log[1]. It contains, among other information, the association between the newly-joined

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[1] Normally, each mote generates a single `mote_create` event. Due to power issues at the manager side, the network restarted a couple of times and new events were created.

device's 8-byte MAC address and its 2-byte `moteId`. The payload size of a `mote_create` serial notification is 6 B.

- **`path_create` and `path_delete`.** In SmartMesh IP terminology, a "path" is the link-layer resource that allows two neighbor nodes to communicate[2]. Each time a mote starts communicating with a new neighbor (e.g. its routing parent), a `path_create` event is produced. Similarly, each time a mote *stops* communicating with a neighbor (e.g. it changes routing parent), a `path_delete` event is produced. We log both messages [11]. The payload size of a `path_create` or `path_delete` serial notification is 9 B.
- **`HR_DEVICE`.** Each network device produces an `HR_DEVICE` every 15 min. This health report contains counters/statistics internal to the mote, such as its current battery voltage, temperature, or total number of messages sent. The payload size of an `HR_DEVICE` serial notification is 27B.
- **`HR_DISCOVERED`.** SmartMesh nodes continuously monitor their surroundings to discover neighbor nodes. Every 15 min, each node produces an `HR_DISCOVERED` health report that contains the list of "discovered" neighbors, and the associate signal strength it heard them at. These discovered neighbors can potentially be used in the future as neighbors the node communicates with. The payload size of an `HR_DISCOVERED` is variable as it depends on the number of neighbors heard.
- **`HR_NEIGHBORS`.** Two nodes are neighbors when link-layer resources are installed for them to communicate. The neighbors of a node are a subset of the discovered neighbors. A SmartMesh IP network is a mesh network, so each mote has multiple neighbors it communicates with. Every 15 min, each mote generates an `HR_NEIGHBORS` health report that contains its list of neighbors. These messages also specify per-neighbor counters, such as the number of link-layer retransmissions. The payload size of an `HR_NEIGHBORS` is variable as it depends on the number of neighbors used.

After 3 months of operation, we have collected 369,276 and 386,929 network statistics in the Smart Agriculture and Smart Building deployment, respectively (see Table 1). The goal of the next section is to present the main results from analyzing this information. We group these results in two categories. "Intuitive" results (Section 5) are results that confirm the performance expected from a SmartMesh IP network. "Not so intuitive" results (Section 6) are results that we believe go against popular belief. This classification is necessarily subjective.

Due to power line failure at the network manager side, the network experienced several restarts. For this reason, some analysis presented in the next sections are done in shorter period. As a beneficial side effect, this allows us to verify the network formation and joining process.

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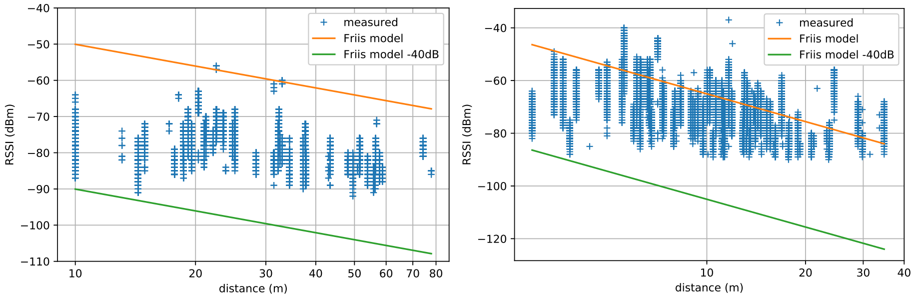
[2] In more classical networking terminology, this is often referred to as a "link". We use the terms "path" and "link" interchangeably in this article.



(a) Smart Agriculture

(b) Smart Building

Figure 4: We observe that the RSSI measurements are roughly located between the Friis model and the Friis model shifted by −40 dB.

5 Intuitive Results

Previous publications [1, 10, 8, 12] underline the performance of TSCH networks in general, and SmartMesh IP in particular. Standardization work in the IETF 6TiSCH working group[3] around TSCH networks further illustrates the move of the industry towards this type of networking technology. While we generally expect good performance from the network, this section verifies that this is the case, on the commercial SmartMesh IP implementation.

We start by looking at two physical-layer metrics: RSSI vs Distance (Section 5.1) and PDR vs. RSSI (Section 5.2). While these have no dependency on TSCH (the type of medium access), they allow us to verify the overall connectivity in the network. We then look at key performance indicators: end-to-end reliability (Section 5.3) and network lifetime (Section 5.4).

5.1 RSSI vs. Distance

The Friis transmission model [13] gives the relationship between the Received Signal Strength (RSSI)[4] in free space. While the Friis transmission model does *not* apply directly to our real-world deployment[5], we observe in Fig. 4 that the individual RSSI values are located between the Friis model, and the Friis model offset by −40 dB. This corroborates the results from [14]. Variability is lower on the Smart Agriculture deployment, given that there is almost no environmental change, compared to what happens on the Smart Building deployment where people move around creating rapid fading changes.

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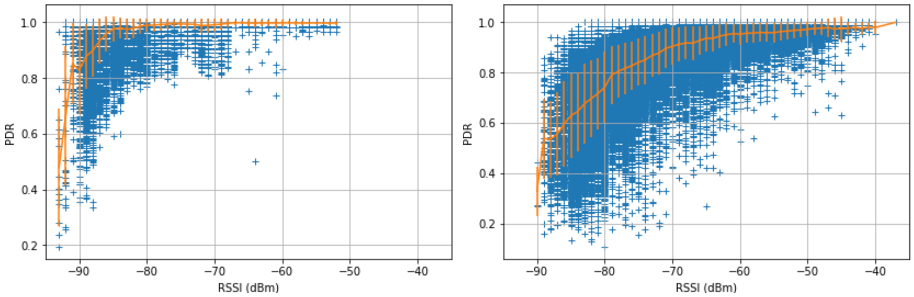
[3] `https://datatracker.ietf.org/wg/6tisch/about/`

[4] Strictly speaking, the RSSI is the Received Signal Strength *Indicator*, a value returned by the radio chip. Because of its prevalence in low-power wireless literature, we use RSS and RSSI interchangeably.

[5] a Log-Normal model would be more appropriate for indoor environment



(a) Smart Agriculture (b) Smart Building

Figure 5: The PDR/RSSI "waterfall" plot. The Smart Building plot is shifted right compared to the Smart Agriculture plot, indicating an environment where external interference is present.

5.2 Wireless Waterfall

Due to the inherent physical unreliability of the radio medium, it is impossible to know if a future transmission will succeed or not. The Packet Delivery Ratio (PDR) is the portion of successful link-layer transmissions over the total number of link-layer transmission attempts. A failed attempt means that the link-layer frame needs to be re-transmitted; this does *not* mean the packet is lost. Over a period of 3 months, 140,897 `HR_NEIGHBORS` messages are collected in the Smart Agriculture deployment and 128,072 in the Smart Building deployment. These contain, for a given node, the number of link-layer transmission attempts and successes to each of its neighbors. We remove the portion of neighbors with no transmission and keep only the DC9003 motes, resulting in a total of 69,643 messages (approx. 49% from the total number of `HR_NEIGHBORS`) for the Smart Agriculture deployment and a total of 93,135 messages (approx. 73%) for the Smart Building deployment.

Fig. 5 plots the PDR and the RSSI of these 69,643 and 93,135 messages. For readability, we also plot the average/deviation of the data for a given RSSI value. Because of its shape, this is known as the "waterfall plot".

For the Smart Agriculture deployment, the average PDR of the links is very good ($>95\%$) above -85 dBm. Below that value, the PDR rapidly degrades, indicating that, on these links, frequent retransmissions happen. For the Smart Building deployment, the PDR starts to degrade at -60 dBm. Note that, if the network were using a non-schedule MAC layer (e.g. ZigBee), the PDR for the same RSSI would be lower than in Fig. 5 because of collisions. The device manufacturer documentation [9] indicates that a path is considered as "bad" when:

- RSSI>-80 dBm and PDR$<50\%$
- RSSI>-70 dBm and PDR$<70\%$

	Smart Agriculture	Smart Building
reliability (Arrived/Lost)	**100%** (693,844 / 0)	**100%** (431,193 / 0)
average PDR (Transmit/Fails)	95% (4,405,569 / 258,778)	87% (19,807,535 / 2,488,149)
latency	700 msec	*not measured.*

Table 2: The overall network performance in the 15-25 July 2016 period (Smart Agriculture) and the 12 Nov. 2016 - 12 Feb. 2017 period (Smart Building).

This is not the case in any of the two deployments.

The waterfall plot allows us to assess the level of external interference. In the presence of external interference, the waterfall plot is either shifted to the right with very few paths below -70 dBm, or does no constantly increase with RSSI.

The waterfall plot in the Smart Agriculture deployment (Fig. 5a) is “clean”, meaning that the SmartMesh IP network is not experiencing high levels of external interference from co-located wireless devices. Especially when comparing both, the waterfall plot in the Smart Building deployment *is* shifted to the right (Fig. 5a), indicating the SmartMesh IP network is experiencing external interference. This is expected, as several hundred WiFi devices and tens of WiFi access points are operating in the building on IEEE802.11 channels 1, 6 and 11.

A fourth type of Health Report allows us to measure the link quality per channel. The `HR_EXTENDED` are generated by each mote every 20 minutes and indicate the number of transmission attempts and link-layer retransmissions *for each frequency*, allowing us to calculate the PDR per channel for each mote. Fig. 6 shows the average PDR collected over a 24-hour period on a business day. During that period, 1402 `HR_EXTENDED` were collected. We can clearly observe the PDR drop of the IEEE802.15.4 links that share the same channel bands as IEEE802.11.

Yet, despite the high external interference, the Smart Building deployment exhibits 100% end-to-end reliability (as detailed in Section 5.3), underlying the resiliency of SmartMesh IP to external interference.

5.3 End-to-End Reliability

We expect the SmartMesh IP network to offer wire-like reliability. Table 2 confirms that this is the case. It presents statistics gathered over the 15-25 July 2016 period in the Smart Agriculture deployment, and over the 12 November 2016 - 12 February 2017 period in the Smart Building deployment. Both sensor data and network statistics are taken into account.

It shows that, as none of the 693,844 and 431,193 packets generated in the networks was lost, the end-to-end reliability is 100%. The average PDR over all links is very high (95% and 87%), indicating that the nodes are deployed close

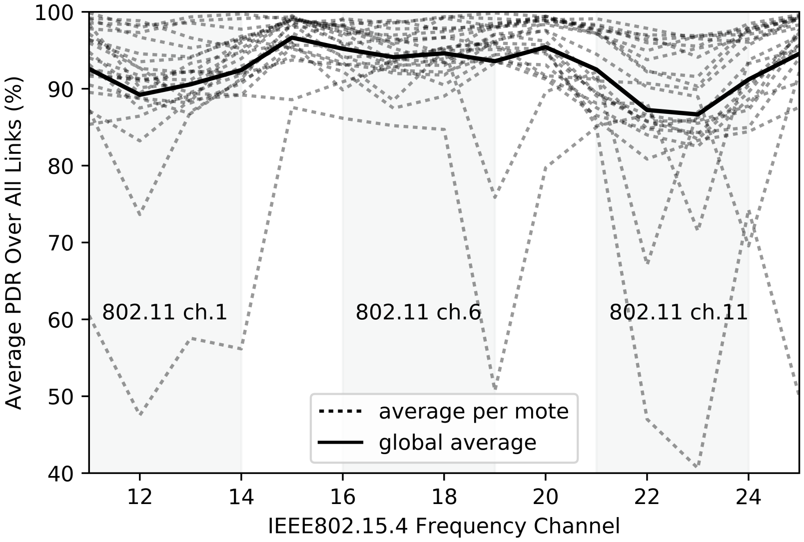


Figure 6: In the Smart Building deployment, external interference from nearby WiFi devices causes some retries (the PDR is lower) *without* impacting end-to-end reliability which stays at 100% (see Section 5.3).

enough to one another. Finally, the average latency over all nodes is 700 ms for the Smart Agriculture deployment. These results are very similar to the very initial results presented in [1], indicating *no* degradation in performance of the SmartMesh IP network over the 3 month periods.

5.4 Network Lifetime

Each device is powered by a pair of Energizer L-91 AA batteries[6]. These contain a nominal 3134 mAh of charge, or 2821 mAh when accounting for a 10% decrease due to manufacturing differences. A SmartMesh IP node contains a "charge accounting" feature in which it tracks the amount of charge it has been drawing from the battery. Each mote reports this number every 15 min as a field in its `HR_DEVICE` health report. This number allows us to predict the lifetime of the device.

Table 3 shows charge consumed by the motes over the two 3 month periods. Assuming a constant energy consumption rate, we extrapolate the lifetime. The nodes with the longest lifetime (8 years) are all leaf nodes as we can see from Fig. 3. Since they do not have to relay data from any children, it is expected for these motes to consume the least. The mote with the shortest lifetime is `30-60-ef`, with a 4 year battery lifetime. This is expected, as this mote relays an important amount of data. This confirms the ultra-low power consumption nature of the SmartMesh IP network.

6 Not so Intuitive Results

Results from Section 5 are "intuitive" in that they corroborate previous measurements [1] or confirm theoretical/lab results [10, 8, 12]. This section presents results which we believe go against popular belief. This classification is necessarily subjective.

In Section 6.1, we show that links are, in fact, symmetrical. In Section 6.2, we show that, through the use of TSCH, the low-power wireless topology is, in fact, extremely stable.

6.1 Link (A)Symmetry

Motes report the average RSSI value of the packets received from each neighbor in their `HR_NEIGHBORS` health reports. Because the network uses channel hopping, the reported RSSI values are also averaged over 15 IEEE802.15.4 frequencies [6]. In this section, we use the term "RSSI" to denote the average RSSI over 15 frequencies.

A common assumption is that links between neighbor low-power wireless devices are hugely asymmetric. That is, on a link between nodes A and B, A receives B's link-layer frames with an RSSI very different from the frames B

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[6] http://data.energizer.com/pdfs/l91.pdf

MAC	charge consumed⋆	lifetime
`30-60-ef`	695 C	4 years
`38-0f-66`	461 C	6 years
`3f-f8-20`	380 C	8 years
`3f-fe-87`	549 C	5 years
`3f-fe-88`	718 C	4 years
`58-32-36`	311 C	7 years
`60-01-f8`	387 C	8 years
`60-02-1b`	371 C	8 years
`60-02-4b`	406 C	7 years
`60-03-82`	395 C	8 years
`60-05-5f`	386 C	8 years
`60-05-69`	509 C	6 years
`60-05-78`	364 C	8 years
`60-05-ab`	381 C	8 years
`60-06-27`	422 C	7 years
`60-08-d5`	432 C	7 years

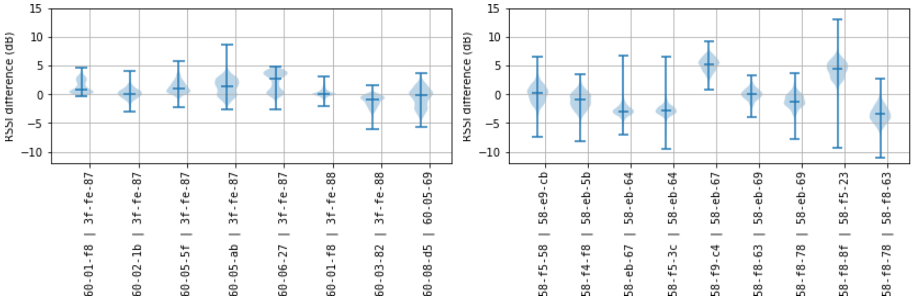
(a) Smart Agriculture

MAC	charge consumed⋆	lifetime
`38-03-dd`	459 C	5 years
`58-e9-ca`	411 C	6 years
`58-e9-cb`	407 C	6 years
`58-eb-5b`	423 C	6 years
`58-eb-64`	322 C	8 years
`58-eb-67`	468 C	5 years
`58-eb-69`	243 C	7 years
`58-f3-17`	357 C	7 years
`58-f4-f8`	402 C	6 years
`58-f5-23`	416 C	6 years
`58-f5-3c`	412 C	6 years
`58-f5-58`	387 C	6 years
`58-f8-63`	198 C	9 years
`58-f8-78`	233 C	7 years
`58-f8-8f`	439 C	6 years
`58-f9-c4`	325 C	8 years

(b) Smart Building

⋆ over the 3.5 month and 3 month periods, respectively.

Table 3: Per-node charge consumed and associated expected lifetime when powered by a pair of AA batteries.



(a) Smart Agriculture

(b) Smart Building

Figure 7: The difference in RSSI between the two directions of the wireless links with the highest number of exchanged messages. The violin plots show the distribution of the value and the standard deviation.

receives from A. Numerous routing protocols (often standardized [15]) reuse that assumption and start with a costly step of filtering out asymmetric links.

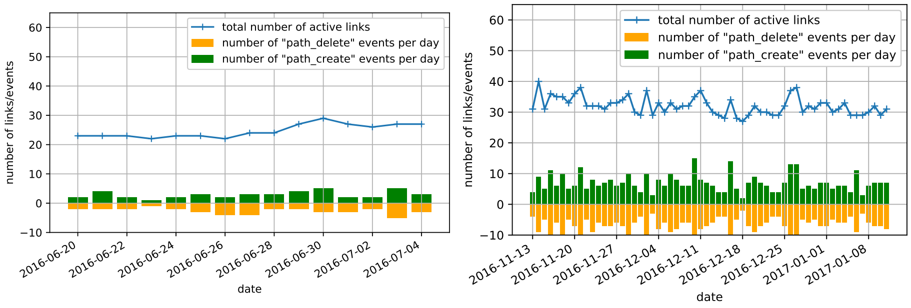
We look at the link statistics between 18 June 2016 and 4 July 2016 (16 days) in the Smart Agriculture deployment, and between the 12 November 2016 and 7 February 2017 (87 days) in the Smart Building deployment. The dataset contains 411,132 `HR_NEIGHBORS` messages received from 14 DC9003 nodes (same hardware). During that period, 21 links are active with at least 250 transmissions for each link. For each of these links, we compute the difference between the average RSSI in each direction. Results are presented in Fig. 7.

In 99.6% of the cases, the difference does not exceed 7 dB. Looking at Fig. 5, this translates into only a handful of percentage points difference in PDR. This means the links can be considered symmetric. This result is in-line with the physical phenomenon that the signal traveling from A to B undergoes the same attenuation as that from B to A. This result would *not* hold if the neighbor radios had a different transmit power or sensitivity. That being said, discussions on link (a)symmetry at the routing layer is largely artificial, as virtually all state-of-the-art medium access control (MAC) protocols uses link-layer acknowledgments, thereby naturally filtering out assymetric links.

6.2 Network Stability

Wireless in unreliable in nature. It is normal that some wireless links interconnecting motes "come and go". That is, links that have been performing well (e.g. PDR>90%) can suddenly disappear (e.g. PDR<10%). Similarly, nodes that were not able to communicate can suddenly hear one another perfectly.

The question, however, is what time scale is considered. Early academic work on low-power wireless [16] has looked at the "burstiness" of the wireless links, i.e. changes over the course of 10-1000's ms. Some follow-up work has taken the assumption that wireless links are so unstable that only a reactive routing approach works. In this section, we infirm this statement by looking at



(a) Smart Agriculture

(b) Smart Building

Figure 8: Network stability: the number of `path_create` and `path_delete` events generated per day over a 16 day (Smart Agriculture) and two month (Smart Building) period. The top line shows the total number of active links.

the stability of the network.

In particular, we look at the `path_delete` and `path_create` events. These are generated each time a node adds/deletes a neighbor to communicate with, which happens for example when the routing topology changes (see Section 4). The number of `path_delete` and `path_create` events is a direct measurement of network stability. We remove the nodes that do not respect the deployment requirement of having at least two parents to associate with (we remove one node in the Smart Agriculture deployment and three nodes in the Smart Building one). Due to the lack of second parent, these nodes were producing over 20 times the amount of messages than all the other nodes combined.

Fig. 8 shows the number of `path_delete` and `path_create` events per day, over the 16 day (Smart Agriculture) and 87 day (Smart Building) periods. For reference, the total number of links in the network is also depicted. There are less than 5 `path_delete` or `path_create` events *per day* in the entire Smart Agriculture network, and at most 15 in the Smart Building network. This means that links, once established, remain useful for days/weeks at a time, and that the network is extremely stable. We attribute the higher churn in the Smart Building deployment to the presence of significant external interference.

This stability can largely be attributed to the use of channel hopping. Changing frequency for each frame is known to efficiently combat multi-path fading and external interference [8], the major causes of instability. If channel hopping were not used, selecting links with high PDR would not be sufficient as they could be affected by external interference at any time and become unstable. It does not contradict the findings of [16], it just means that link-layer retransmissions can efficiently cope with link burstiness, and that the multi-hop topology can remain very stable.

7 Conclusion

This article analyzes the network statistics generated by two low-power wireless mesh networks deployed in real-world conditions. The first network is deployed in a peach orchard in Argentina, in a Smart Agriculture scenario. Its 21 motes have produced 369,276 statistic measurements over the course of 3.5 months. The second network is deployed in an office building in Paris, in a Smart Building scenario. Its 17 motes have produced 386,929 statistic measurements over the course of 3 months.

We use a "waterfall" plot to show that the two networks are subject to different amounts of external interference from other wireless devices deployed in the same area. The SmartMesh IP network delivers its exceptional performance, with 0 packets lost out of 693,844 (Smart Agriculture) and 431,193 (Smart Building) received (100% reliable) and 4-8 years of battery lifetime on a pair of commercial AA batteries. This is representative of the performance of 6TiSCH technology.

While it is often assumed that wireless links are asymmetric, we show to the contrary that the difference in RSSI averaged over 15 IEEE802.15.4 channels does not exceed a handful of dB. We show that the network is extremely stable, with less than 5 links being added or deleted per day in the Smart Agriculture deployment, at most 15 in the Smart Building deployment. We attribute this performance to the use of Time Synchronized Channel Hopping (TSCH) technology at the heart of the SmartMesh IP products.

We conclude that SmartMesh IP is a perfectly suitable IoT solution for Smart Agriculture and Smart Building applications.

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