Jam-X: Wireless Agreement under Interference

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ABSTRACT

Wireless low-power transceivers used in sensor networks such as IEEE 802.15.4 typically operate in unlicensed frequency bands that are subject to external interference from devices transmitting at much higher power. Communication protocols should therefore be designed to be robust against such interference. A critical building block of many protocols at all layers is agreement on a piece of information among a set of nodes. At the MAC layer, nodes may need to agree on a new time slot or frequency channel; at the application layer nodes may need to agree on handing over a leader role from one node to another. Message loss caused by interference may break agreement in two different ways: none of the nodes use the new information (time slot, channel, leader) and stick with the previous assignment, or – even worse – some nodes use the new information and some do not. This may lead to reduced performance or failures.

In this paper we investigate the problem of agreement under interference and point out the limitations of the traditional message-based n-way handshake approach. We propose novel protocols that use jamming instead of message transmissions and show that they outperform the n-way handshake in terms of agreement probability, energy consumption, and time-to-completion both in the unicast case (two neighboring nodes agree) as well as in the broadcast case (any number of neighboring nodes agree).

1. INTRODUCTION

Wireless sensor nodes often need to agree on fundamental pieces of information that can drastically affect the performance of the network. Several state-of-the-art MAC protocols use time division multiple access (TDMA) or frequency diversity techniques to optimize their performance, in order to maximize network lifetime and minimize battery depletion. In such protocols, vital information such as the TDMA schedule, the channel-hopping sequence derived by interference-aware protocols, or the seed used to regulate the random channel hopping need to be agreed upon by two or more sensor nodes in a reliable fashion. Failure to agree on such information correctly (e.g., nodes using inconsistent TDMA schedules) may lead to a disruption of the network connectivity or to a substantial performance degradation.

When sharing information using an unreliable medium (such as wireless), no delivery guarantee can be given on the messages that are sent. Akkoyunlu et al. [1] have shown that, in an arbitrary distributed facility, it is impossible to provide the so called complete status, i.e., one cannot guarantee that two distributed parties know the ultimate fate of a transaction and whether they are in agreement with each other.

The problem is further exacerbated in the presence of external interference: the low-power transmissions of wireless sensor networks are highly vulnerable to interference caused by radio signals generated by devices operating in the same frequency range. Several studies have highlighted the increasing congestion of the unregulated ISM bands used by sensornets to communicate, especially the 2.4 GHz band [2]. Sensornets operating on such frequencies must cope with simultaneous communications of WLAN and Bluetooth devices, as well as with the electromagnetic noise generated by domestic appliances such as microwave ovens.

Hence, it is important to derive reliable techniques to ensure agreement among nodes and make sure that they are robust to external interference. At the same time, these techniques need to be efficient since sensor nodes have limited computational capabilities and energy resources.

Traditional communication protocols make use of one or more acknowledgment messages to verify whether the information was successfully shared (e.g., TCP handshake). We show that this approach is not optimal under external interference for two main reasons. Firstly, the probability of receiving a packet correctly is small, and therefore the chances of receiving successfully an entire sequence of acknowledgment packets is even lower. Secondly, the overhead intro-
Two battalions are encamped near a city, ready to launch the attack. Because of the redoubtable fortifications, the attack must be carried out by both battalions at the same time in order to succeed. Hence, the generals of the two armies need to agree on the time of the attack, and their agreement must be carried out by both battalions at the same time. It is their final attack. Because of the redoubtable fortifications, the communication channel is unreliable. Each general must be aware that the other general has agreed on the attack plan, messengers are used also to exchange acknowledgments. However, because the acknowledgement of a message receipt can be lost as easily as the original message, a potentially infinite series of messages is required to reach an agreement. A different problem that we are not addressing in this work is how to guarantee the identity of the sender of the message, as well as how to cope with misbehaving parties.

2.1 Agreement in Wireless Networks

In the context of wireless communications, the problem can be rephrased as follows. When two nodes, S and R, need to agree on a common value V, they exchange a sequence of n messages in an alternating manner (Figure 1). Node S is the initiator of the exchange. After the transmission of V, each message acknowledges the receipt of the former message, i.e., a node sends a message i > 1 only if it correctly received message i−1. There are no retransmissions, i.e., if a message is lost, the exchange is terminated. Each node uses a simple rule to determine the success of the exchange: if all expected messages are received, the exchange is deemed successful, otherwise the exchange is deemed unsuccessful.

Please note that this scenario corresponds to an n-way handshake between nodes S and R, where n is the number of packets exchanged. The n-way handshake is a widely used mechanism in communication networks. For example, TCP employs a 3-way handshake (n=3) to establish connections over the network, whereas IEEE 802.11i (WPA2) uses a 4-way handshake (n=4) to carry out the key exchange.

This scenario leads to three possible outcomes:

1. **Positive Agreement.** The n messages are all received correctly, and both nodes deem the exchange as successful, accepting V.

2. **Negative Agreement.** A message m with m < n, i.e., a message prior to the last message n, is lost. None of the two nodes receives all the expected messages, hence both nodes deem the exchange as unsuccessful, discarding V.

3. **Disagreement.** The message n, i.e., the last message, is lost. One of the two nodes receives all the expected messages, and deems the exchange as successful, while the second node misses the last message and therefore deems the exchange as unsuccessful.
In the original two generals’ scenario, a positive agreement would lead to a simultaneous attack of the city by both battalions and a consequent victory, a negative agreement would cause both battalions to stall, while a disagreement would trigger the attack of only one battalion, and a consequent defeat of the attacking forces.

Notice that while a disagreement is a potentially pernicious outcome, a negative agreement is often less severe. For example, if the shared value contains the next wireless channel to be used for communication, two nodes are better staying in the same lossy wireless channel, rather than having only one of them move to a different channel. The probability of negative agreements should, however, be minimized, as it may lead to reduced performance.

The frequency of the three outcomes described above is strongly dependent on the link quality. Letting $p$ represent the probability that a generic message is successfully received (assuming that $p$ remains constant over time and that it is independent for each packet), and $n$ the length of the n-way handshake, we obtain:

\[
\begin{align*}
\text{Prob}(\text{Positive Agreement}) &= p^n \\
\text{Prob}(\text{Negative Agreement}) &= 1 - p^{n-1} \\
\text{Prob}(\text{Disagreement}) &= p^{n-1}(1 - p)
\end{align*}
\]

Figure 2 illustrates the distribution of the probabilities of positive agreement (a), negative agreement (b), and disagreement (c), as a function of the probability $p$ of successful packet exchanges instead. Redundant packet transmissions (i.e., repeating a handshake message several times and assuming successful transmission if at least one copy is received) can achieve this, but are not advisable as they also increase energy consumption.

Another aspect that affects $p$ is the channel quality itself. Unfortunately, sensor motes operate in unlicensed ISM radio bands, and often use a very low transmission power, which makes them vulnerable to external interference. Any wireless appliance operating in the same frequency range of sensor motes can potentially interfere with their communications and therefore radically decrease the probability of successful packet exchange $p$. In the 2.4 GHz ISM band, for example, Wi-Fi and Bluetooth networks as well as domestic appliances such as microwave ovens can create noise levels that overwhelm the interference resistance capabilities of DSSS radios and radically decrease the packet reception rate [2,4].

Hence, we will investigate ways to encode transmissions such that their success probability $p$ is maximized for interfered channels. However, for this we first have to understand the characteristics of interfered channels.

### 2.2 Agreement in Wireless Sensor Networks Challenged by External Interference

In the context of wireless sensor networks, minimizing the amount of exchanged packets $n$ is mandatory because of the limited energy resources available on sensor nodes, i.e., one needs to minimize the time in which the radio is active as much as possible. Hence, one should try to maximize the probability $p$ of successful packet exchanges instead. Redundant packet transmissions (i.e., repeating a handshake message several times and assuming successful transmission if at least one copy is received) can achieve this, but are not advisable as they also increase energy consumption.

Besides minimizing the chances of disagreement, long n-way handshakes also increase the probability of negative agreement, especially when dealing with unreliable channels. For this reason, minimizing the amount of disagreements while maximizing the amount of positive agreements becomes a catch-22 dilemma in the presence of unreliable links. Figure 2 shows that long n-way handshakes minimize both the probability of disagreement and the probability of positive agreement, while short n-way handshakes maximize both the probability of positive agreement and the chances of disagreement.

### 2.3 Analysis of Common Interference Sources

In order to understand and mitigate the impact of external interference on the probability of successful transmission $p$ in wireless sensor networks communications, we study...
the interference patterns produced by common devices operating in the 2.4 GHz ISM band. We perform a high-speed sampling of the RSSI register of the CC2420 radio (≈ 50 kHz as in [5]) using Maxfor MTM-CM5000MSP and Sentilla Tmote Sky motes. We call this operation fast RSSI sampling over a time window \( t_{\text{samp}} \). Figure 3 shows the outcome of fast RSSI sampling both in the presence of sensornet communications and external interference.

**Absence of external interference.** When neither interference nor IEEE 802.15.4 packet transmissions are present, the fast RSSI sampling returns the so called noise floor. The latter has typically values in the proximity of the radio sensitivity threshold (e.g., in the range \([-100, -94]\) dBm for the CC2420). In the presence of IEEE 802.15.4 packet transmissions, fast RSSI sampling returns values that correspond to the received signal strength upon packet reception (the same value that would be returned by the RSSI indicator) lasting for the duration of the transmission (Figure 3(a)). As packets have a constrained maximum payload size of 127 bytes according to the 802.15.4 PHY standard, a packet transmission with 250 Kbit/sec will not last more than \( \approx 4.3 \) ms.

**Presence of external interference.** In the presence of interference, fast RSSI sampling can return different outcomes that depend on several variables. For example, Wi-Fi traffic depends on the number of active users and their activities, and on the traffic conditions in the backbone.

Figure 3(b) shows the outcome of fast RSSI sampling in the presence of heavy Wi-Fi interference (caused by a file transfer). The transmissions of Wi-Fi devices are much stronger than sensornet transmissions, and can affect several IEEE 802.15.4 channels at the same time. Hauer et al. [6][7] have shown that with a sufficiently high sampling rate, one can identify the short instants in which the radio medium is idle due to the Inter-Frame Spaces (IFS) between 802.11 packets. Figure 3(b) shows that it is indeed possible to identify RSSI values matching the radio sensitivity threshold between consecutive Wi-Fi transmissions.

Figure 3(c) shows an example of interference generated by Bluetooth. The latter uses an Adaptive Frequency Hopping mechanism to combat interference, and hops among 1-MHz channels around 1600 times/sec., hence it remains in a channel for at most 625 \( \mu \)s. Since Bluetooth channels are more narrow than the ones defined by the 802.15.4 standard, it may happen that communication in multiple adjacent Bluetooth channels affects a single 802.15.4 channel.

Figure 3(d) shows an example of the interference pattern caused by microwave ovens. Microwave ovens emit high-power noise (≈ 60 dBm) in the 2.4 GHz frequency band in a very periodic fashion: the duration of their interference does not last more than \( \approx 10 \) ms before being followed by \( \approx 10 \) ms quiescence [5].

**The role of idle periods.** In the presence of interference, \( n \)-way handshakes need to take advantage of idle periods. In principle, the longer the idle period and the shorter the exchange sequence, the higher the likelihood of obtaining positive agreements. However, the interplay between idle periods and \( n \)-way handshakes is complex because of the particular pattern of each interfering source. Some devices, such as microwave ovens, present periodic patterns with relatively long idle periods, while others, such as Wi-Fi stations, can present shorter idle periods with a highly variable and random length. For our purposes, we characterize an interfering source based on the random variables \( IDLE_i \) and \( BUSY_i \), which denote the distributions of the idle and busy periods.

Our aim is to encode part of the handshake messages such that they can be successfully received despite interference and for different distributions of idle and busy periods as detailed in the subsequent section.

3. **JAMMING AS BINARY ACK SIGNAL**

The \( n \)-way handshake shown in Figure 1 conveys the information \( V \) to be agreed upon only in the first message, whereas the remaining messages are only used to acknowledge its reception. The acknowledgment packets carry essentially only two pieces of information: (i) the confirmation of the receipt and (ii) the identity of sender and receiver.

Based on the discussion in the previous section, all messages should be as short as possible to increase the chances of fitting into idle periods. With respect to this, the encoding of acknowledgements in IEEE 802.15.4 messages is very inefficient. While their payload consists of a single ACK bit, the whole packet consists of synchronization preamble and a physical header (4-bytes preamble, 1-byte SFD, 1-byte length field) as well as a MAC header (2-bytes frame control, 1-byte sequence number, 4-20-bytes address, 2-bytes FCS,
0–14 bytes auxiliary security header). If any of the bits in the headers and preamble are corrupted by external interference, the packet is often undecodable [8, 9].

Therefore, instead of encoding acknowledgements as packet transmissions, we propose to encode acknowledgements by jamming, where the presence of jamming signals is known in advance as discussed further below.

Figure 4: RSSI values recorded during the transmission of a jamming sequence without external interference (a), and with external Wi-Fi interference (b).

While a jamming signal can encode the binary acknowledgement information, it cannot encode the identities of the sender and receiver as we will show in the remainder of this section.

The key advantage of this approach is that jamming as generated by off-the-shelf mote radios can be reliably detected even under heavy interference as we will show in the remainder of this section.

As highlighted in Section 2, common radio chips offer the possibility to read the RSSI in absence of packet transmissions – the so-called RSSI noise floor measurement or energy detection feature. Several researchers have shown that it is a useful way to assess the noise and the level of interference in the environment [4, 7, 11]. RSSI readings close to the sensitivity threshold of the radio indicate absence (or a limited amount) of interference, while values above this threshold identify a packet transmission, or a busy/congested medium (Figure 4).

We sample the RSSI register at high frequency to detect the presence or absence of a jamming signal generated by a sensor node. As shown in Figure 4(a), a jamming sequence lasting for a time window \( t_{\text{jam}} \) results in a stable RSSI value above the sensitivity threshold of the radio, very similar to a packet transmission (shown in Figure 3(a)). Therefore, if any of the RSSI samples equals the sensitivity threshold of the radio, no jamming signal is present.

In the presence of additional external interference, the RSSI register will return the maximum of the jamming signal and the interference signal due to the co-channel rejection properties of the radio [5]. Figure 4(b) illustrates this for a jamming signal with simultaneous Wi-Fi interference. As we have shown in Section 2.3, typical interference sources – in contrast to our jamming signal – do not produce continuous interference for long periods of time, rather they alternate between idle and busy. That is, if the jamming signal lasts longer than the longest busy period of the interference signal, we are still able to detect the absence of the jamming signal by checking if any of the RSSI samples equals the sensitivity threshold of the radio.

4. JAM-X: WIRELESS AGREEMENT UNDER INTERFERENCE

In this section, we present Jam-X, a family of jamming-based protocols designed to provide a high probability of agreement in the presence of heavy external interference.

4.1 Jam-2: 2-Way Handshake with Jamming

As highlighted in Section 2 due to the constraints of wireless sensor networks we need to minimize the amount of exchanged packets. For \( n = 2 \) we obtain a two-way handshake protocol shown in Figure 5(a) where node \( S \) initiates the transmission and sends the value \( V \) to node \( R \), and node \( R \) acknowledges the receipt of \( V \) with a new transmission towards \( S \). We refer to this protocol as Ack-2.
We call Jam-2 the two-way handshake in which the acknowledgment is sent in the form of a jamming sequence (Figure 5(b)). Node $S$ initiates the exchange and sends the information $V$ towards a receiver $R$ (Figure 5(b)). If the first message is successfully received, $R$ transmits a jamming signal for a period $t_{jam}$. Meanwhile, $S$ carries out a fast RSSI sampling for a period $t_{samp} \leq t_{jam}$ that is synchronized in such a way that the fast RSSI sampling is carried out while the jamming signal is on the air. The first message, i.e., the one containing the information $V$, is used as the synchronization signal. For our purposes, this is sufficient since clock drift is insignificant at timescales of a few milliseconds. Hence, for simplicity, in the rest of the paper we assume $t_{jam} = t_{samp}$.

Denoting $r_{noise}$ as the maximum RSSI noise floor value measured in the absence of interference, and $\{x_1, x_2, \ldots, x_n\}$ as the sequence of RSSI values sampled during $t_{samp}$, we define the binary sequence $\{X_1, X_2, \ldots, X_n\}$ as follows: if $x_i \leq r_{noise}$, then $X_i = 1$, else $X_i = 0$. If $\sum_{i=1}^{n} X_i = 0$, the initiator $S$ assumes that a jamming sequence was transmitted by node $R$.

Note that the received signal strength $r_{jamming}$ of the jamming sequence has to be higher than $r_{noise}$. Therefore, the selection of $r_{noise}$ is important, especially for low-quality links, where $r_{jamming}$ will have a value very close to $r_{noise}$.

In order for Jam-2 to be successful (positive agreement), two conditions must be satisfied: (i) the packet from node $S$ to node $R$ must be successfully decoded and (ii) node $S$ must correctly detect the presence of the jamming signal and not confuse it with any other external interference signal.

Condition (i) depends on the interplay of $IDLE_i$ (length of idle periods in the interference signal) and the duration $t_{V}$ of the transmission of the packet containing $V$. A necessary condition for receiving this message is $t_{V} < \max\{IDLE_i\}$. If $R$ cannot successfully decode the packet, $R$ does not transmit any jamming sequence. The success of condition (ii) depends on the interplay of $BUSY_i$ (length of busy periods in the interference signal) and the duration $t_{jam}$ of the jamming signal. As discussed in Section 3.2, a necessary condition for correctly detecting the jamming signal is $t_{jam} > \max\{BUSY_i\}$.

Increasing the duration $t_{jam}$ of the jamming signal leads to longer delays and a higher energy consumption. Having $t_{jam} < \max\{BUSY_i\}$ may imply that $X_i$ is always 0, and $S$ concludes that a jamming sequence was transmitted even though it was not. This scenario may lead to disagreement that we call false positive agreement when $R$ does not receive the packet containing $V$ and does not transmit any jamming sequence, but the interference lasts for a period longer than $t_{jam}$.

In order for Ack-2 to be successful (positive agreement), both the packet from $S$ to $R$ and the acknowledgment packet from $R$ to $S$ must be successfully decoded. The success of the exchange depends on the interplay of $IDLE_i$ and the transmission delays ($t_{V}$ and $t_{ack}$, see also Section 4.3).

4.2 Jam-3: 3-Way Handshake with Jamming

When using Jam-2, node $S$ can confuse external interference resulting in RSSI values greater than $r_{noise}$ with the jamming sequence transmitted by node $R$. Having an approximate knowledge of the signal strength $r_{jamming}$ of the jamming sequence would enable $S$ to filter out RSSI values $r_{noise} < x_i < r_{jamming}$ that lead to $X_i = 1$ in Jam-2, therefore reducing the probability of a false positive agreement.

Therefore we consider a 3-way handshake, where $R$ can exploit knowledge of the RSSI of the first received packet to enhance the detection of a later jamming sequence, assuming that the two should have similar received signal strength. The rest of this section describes Jam-3, a three-way handshake protocol where the last acknowledgment is implemented with jamming as shown in Figure 5(c).

Node $S$ initiates the exchange and sends the information $V$ towards a receiver $R$. If the first message is received successfully, $R$ sends an acknowledgment packet back to $S$. If $S$ receives the ACK, it transmits a jamming signal for a period $t_{jam}$. Meanwhile, $R$ carries out a fast RSSI sampling for a period $t_{samp} \leq t_{jam}$ (Figure 5(c)). If the receiver detects the jamming signal from the sender it deems the exchange as successful; otherwise, $V$ is discarded.

The advantage of this approach compared to Jam-2 is that $R$ knows the received signal strength of the first packet $r_s$. Under the hypothesis that the jamming signal has a reasonably similar strength as $r_s$, $R$ filters out RSSI values $r_i < r_s$ that must have been generated by external interference.
Hence, denoting \( \{x_1, x_2, \ldots, x_n\} \) as the sequence of RSSI values sampled during \( t_{\text{amp}} \), we define the binary sequence \( \{X_1, X_2, \ldots, X_n\} \) as follows: if \( x_i < (r_s - \Delta_r) \), then \( X_i = 1 \), else \( X_i = 0 \), where \( \Delta_r \) is a threshold to account for slight variations in the signal strength. If \( \sum_{i=1}^{n} X_i = 0 \), \( R \) assumes that a jamming sequence was transmitted by \( S \).

Due to the inaccuracy of low-power radios, a tolerance margin \( \Delta_r \) must be provided, and its role is crucial. If \( (r_s - \Delta_r) < r_{\text{noise}} \), then the algorithm assumes \( r_s := r_{\text{noise}} \), resulting in the same behavior as in Jam-2. Compared to Jam-2, Jam-3 can provide a higher accuracy because it exploits the information provided by \( r_s \). As with Jam-2, false positive agreements can be removed if \( t_{\text{jam}} > \max\{BUSY\} \) at the expense of a higher energy consumption.

### 4.3 Jam-X Implementation

We implement Jam-X on the Tmote Sky platform that features a CC2420 radio 12 and an MSP430 microprocessor. Our implementation, based on Contiki 13, uses two main building blocks, i.e., the generation of the jamming sequence and the high-frequency RSSI sampling.

The generation of the jamming sequence uses the CC2420 transmit test modes as described in Section 3.3. This specific feature of the CC2420 transceiver is also available on other nodes such as the Ember EM2420 and the CC2520 5. Similar to Boano et al. 5 we implement the high-frequency RSSI sampling by boosting the CPU speed and optimizing the SPI operations. This way, we obtain one RSSI sample approximately every 20 \( \mu s \). The achieved sampling rate of about 50 KHz does not capture the transmissions from all other devices operating in the same frequency band such as IEEE 802.11n. Nevertheless, we can still identify most of the idle instants between Wi-Fi transmissions which allows us to distinguish the jamming sequence from external interference as discussed in Section 3.3.

For the experiments we use NULLMAC, a MAC layer that just forwards packets to the upper or lower protocol layer and does not perform any duty cycling. We chose NULLMAC in order to obtain results that are independent of specific MAC features and parameters. Before sending a message, a Clear Channel Assessment (CCA) is performed to minimize the chances that the packet is destroyed by interference. For the initial handshake message containing \( V \), \( S \) waits until the CCA signals an idle medium. At this point, the initiator of the handshake transmits the first packet.

Before transmitting subsequent ACK packets (but not before jamming), a CCA check is performed once and the packet is only transmitted if the medium is idle. The reason for not waiting until the channel clears is that this would introduce unbounded delays such that it could not be decided if the acknowledgement is lost or just arbitrarily delayed.

### 5. UNICAST EVALUATION

In this section, we evaluate the performance of Jam-2 and Jam-3 by comparing it with the performance of packet-based handshakes for unicast agreement.

#### 5.1 Experimental Setup

In order to evaluate the performance of Jam-X, we carry out experiments in two small-scale indoor testbeds deployed in office environments with USB-powered motes. In the first testbed, we use JamLab, a tool for controlled interference generation 5 to evaluate the impact of interference in a realistic and repeatable fashion. In JamLab, interference is either replayed from trace files that contain RSSI values recorded under interference, or from models of specific devices 5. In particular, we use JamLab to emulate the interference patterns produced by microwave ovens, by Bluetooth, and by Wi-Fi devices. In the latter case, the interference emulates a continuous file transfer. To avoid additional interference as much as possible, we carry out the experiments in this testbed during the night, when Wi-Fi activity in the office building is lowest. In the second testbed, we do not use JamLab, but we deliberately choose an 802.15.4 channel affected by interference, namely channel 18. On channel 18 there is Wi-Fi traffic and sometimes also interference from microwave ovens in a nearby kitchen.

For the experiments, we use two motes \( S \) and \( R \). Node \( S \) initiates the handshake, and transmits a data packet \( V \) composed of a 4-byte sequence number and one additional byte containing the transmission power used. For each handshake, we select a random transmission power between -25 dBm and 0 dBm. \( R \) replies to the message using the transmission power contained in the packet, i.e., the same one used by \( S \). By using different transmission powers, we create different types of links for each handshake. Each packet is sent after a random interval in the order of tens of milliseconds, and nodes remain on the same channel for the whole duration of the experiment. Each experiment consists of several hundred thousand handshakes.

#### 5.2 Generic n-way Handshake

Using JamLab, we analyze the performance of a generic n-way handshake under different interference patterns. Fig. 6 and 7 show the percentage of positive/negative agreements and disagreements under interference for n-way handshakes, i.e., the protocol shown in Fig. 1 with up to \( n = 8 \) packets.

The results match very well the trends of the theoretical results shown Figure 8. When \( n \) increases, the probability of both disagreements and positive agreements decreases. The probability of negative agreements grows with \( n \).

As expected, under microwave oven interference (that has a periodic pattern with idle and busy durations of \( \approx 10 \) ms), positive agreement cannot be reached when \( n \geq 3 \). This is because the duration of the handshake is longer than the idle period, hence interference will hit at least one of the packets.
We now compare the performance of 2-way handshakes based on packet transmissions (Ack-2) and jamming sequences (Jam-2). Figure 6 shows the performance of Ack-2 under interference. As discussed in Section 2.2, we investigate the case where a train of Ack-2 acknowledgement packets is sent to increase the probability of successful reception. The case in which \( T = 1 \) corresponds to the 2-way handshake depicted in Figure 5(a).

It is important to highlight two aspects related to sending a train of acks. Firstly, having \( T > 1 \) improves the probability of positive agreements. Secondly, sending a train of \( k \) packets is much faster than performing a \( k \)-way handshake as the packet can be loaded once into the radio and then transmitted several times, thus avoiding the overhead for receiving, decoding, extracting, analyzing, processing the packet and generating the response. Due to this reason, we can send more repeated ACKs during the idle time of the microwave than we can send handshake messages.

Figure 7 shows the probability of positive/negative agreements and disagreements under interference for Jam-2. After receiving the first packet, \( R \) transmits a jamming sequence of length \( t_{\text{jam}} \). Obviously, the longer the jamming sequence lasts, the higher the probability of successful agreement.

Observe the following two important aspects. Firstly, the probability of disagreements with Jam-2 is much lower than that of Ack-2 even for short jamming periods \( t_{\text{jam}} \). Secondly, in Ack-2 the amount of negative agreements is basically independent on \( T \), and with increasing \( T \) an increasing fraction of the disagreements is replaced by positive agreements. Instead, with Jam-2, the amount of positive agreements remains constant and reaches the maximum already with short \( t_{\text{jam}} \). With increasing \( t_{\text{jam}} \), an increasing fraction of the disagreements is replaced by negative agreements. This is because in Jam-2 the detection of a jamming signal is very reliable, and the disagreements basically occur only when the first packet is lost – resulting in negative agreement.

We now investigate the energy consumption and time to completion of Jam-2 and Ack-2. For this purpose, we first measure the transmission delay (i.e., the time in which the message is actually over the air) as a measure of transmit power consumption. Secondly, we measure the time that is actually required by the operating system to complete the unicast_send command. To achieve this goal, we use Contiki’s software-based power profiler [14]. The second value is larger than the first one, because it includes the processing of the packet and its loading into the radio buffer before the

5.3 2-way Handshakes: Ack-2 and Jam-2

The handshake before interference starts again. Therefore, in the remaining experiments we always perform CCA before sending the first packet.
packet actually gets transmitted over the air.

Figure 10(a) shows the results. For a payload of one byte (i.e., for a generic ACK message), we obtain a transmission delay of 782 µs and a processing + sending time of 2083 µs. Based on these two values, we plot the fraction of disagreements under different interference patterns as a function of the time to complete the agreement (Figure 10(b)) and as a function of transmit power consumption (Figure 10(c)). While we can continuously vary \( t_{jam} \) in Jam-2, for Ack-2 we can only vary the number \( T \) of ACK messages in the train, resulting in discrete boxes in the figures that are drawn to scale. We see that Jam-2 results in a substantially smaller fraction of disagreements compared to Ack-2 for a given time-to-completion and for a given power consumption.

We also evaluate the performance of Jam-2 under real interference by running an experiment in our second testbed, deployed in an environment rich of Wi-Fi traffic and noise generated by microwave ovens. We implement a program that carries out continuous handshakes both using Ack-2 and using Jam-2 (the latter uses a \( t_{jam} = 2 \) ms), and run it over several days, carrying out more than 1 million handshakes.

Figure 11 shows the results of our experiment. The top figure shows the performance of Ack-2 and Jam-2 in terms of the fraction of disagreements. The bottom figure shows the Channel Quality metric (CQ), that provides an estimate of interference by capturing a channel’s availability over time \[ CQ \]. The figure shows that Jam-2 has a very low fraction of disagreements compared to Ack-2. Both Jam-2 and Ack-2 have the worst performance around noon during weekdays (Oct. 16 was a Sunday). During these times, the fraction of disagreements for Jam-2 grows to 0.5%, while it is close to 0% at other times. We attribute this bad performance during lunch to the microwave ovens in the nearby kitchen (\( t_{jam} < BUSY_{oven} \)). The bottom graph shows that the channel quality is actually lower when the fraction of disagreements is high, i.e., during noon on weekdays.

5.4 3-way Handshakes: Ack-3 and Jam-3

We evaluate the performance of Jam-3 in our JamLab-based testbed and compare it against a traditional packet-based 3-way handshake Ack-3. The main difference between Jam-2 and Jam-3 is that in Jam-3 the receiver uses the RSSI of the initiator’s first packet \( r_s \) to improve the detection of the subsequent jamming signal as described in Sect. 4.2. Our fo-
6. JAM-B: BROADCAST AGREEMENT

In certain cases, e.g., when agreeing on time slots in a MAC protocol, a node $S$ needs to agree with a set of $r > 1$ neighboring nodes. By exploiting jamming and following the principles described in Section 4, we design Jam-B, a protocol to reach agreement in broadcast scenarios.

Jam-B performs a 3-way handshake as depicted in Figure 13. First, $S$ broadcasts the initial packet containing $V$ to its $r$ neighbors $R_i$. Then, each of these nodes computes a bit vector $BV$ holding $k \geq r$ bits as a function of its node address. This bit vector is then interpreted as a TDMA schedule with $k$ slots, that is, a node jams during slot $i$ if and only if $BV[i] = 1$. The encoding of the bit vectors must be such that the overlay of all nodes $R_i$ jamming simultaneously results in a continuous jamming signal at $S$. As in Jam-2, $S$ samples RSSI during all slots. If a jamming signal is detected in all slots, $S$ jams in turn for $t_{jam}$ and all neighbors sample RSSI to detect this jamming signal.

Besides the choice of the duration $t_{slot}$ of one jamming slot, the encoding of the bit vectors affects the detection accuracy. In the simplest case, the number of slots equals the number of neighbors and every neighbor has exactly one bit set to 1 in its bit vector. However, a better alternative is to use more slots than neighbors (possibly trading off more slots for a shorter slot duration $t_{slot}$) and use an encoding that sets multiple bits to 1 in each neighbors’ bit vector maximizing the distance between the bits. This approach reduces the chances that interference affects all the jamming slots of a node. We leave the derivation of an optimal encoding scheme for future work.

6.1 Jam-B Implementation

We implement Jam-B on the same platforms described in Section 4. In our implementation, the bit vector consists of 16 bits. A slot has a fixed duration $t_{slot} = 1000\mu$s, which corresponds to roughly 49 RSSI samples. Only a subset of those samples is used by $S$ to assess the presence of jamming due to synchronization inaccuracies. While the initial broadcast message acts a synchronization beacon for the nodes, packet processing delays, radio settling times, and RSSI readout latency (about 21 $\mu$s) lead to variable time offsets among the nodes. Also, slot sizes are not an integral multiple of the RSSI sampling interval. Finally, the RSSI values need a time of about 128 $\mu$s to settle. Therefore, we introduce a guard time $t_{sett}$ of 8 RSSI samples or 169 $\mu$s between slots during which RSSI samples are discarded. We use $t_{jam} = 2$ ms.
Figure 12: Performance of Jam-3 and Ack-3 under Bluetooth interference (a), and role of $\Delta_r$ for Jam-3’s efficiency (b).

Figure 13: Illustration of Jam-B.

For the bit vector encoding, we chose a scheme where each node $R_i$ sets $\left\lfloor \frac{16}{r} \right\rfloor$ bits to 1 in its bit vector such that no pair of nodes has a one bit at the same position. Each of the remaining $16 - \left\lfloor \frac{16}{r} \right\rfloor$ bits is allocated to multiple nodes in a symmetric fashion. The positions of the bits to 1 in each $BV[i]$ are chosen such that their distance is maximized.

6.2 Evaluation

We evaluate Jam-B using the same experimental setup described in Section 5.1. We select 7 motes from the Jam-Lab testbed, one of them as the sender $S$, and the remaining 6 as receivers. We run the experiment under the different interference patterns used previously. We compare Jam-B with its equivalent Ack-B implemented using ACK packets instead of jamming. Figure 14 shows the results, where Jam-B clearly outperforms Ack-B. The latter leads to a very high number of negative agreements because of the high probability that at least one of the packets involved in the exchange gets corrupted. The gain obtained using Jam-B is therefore much bigger compared to simple unicast scenarios.

7. RELATED WORK

Agreement is a well-known problem in distributed systems. Pioneering work in the late 1970s highlighted the design challenges when attempting to coordinate an action by communicating over a faulty channel [1, 3].

In the context of wireless sensor networks, the agreement problem has not been been widely addressed. The main focus has been on security for the exchange of cryptographic keys [16], and on average consensus for nodes to agree on a common global value after some iterations [17]. Similarly to these studies, our work aims at protocols that allow a set of nodes to agree on a piece of information, but our study has two distinctive characteristics, we focus: (i) on overcoming the effects of common interference signals and (ii) on solutions that fit applications with timeliness requirements.

Our work is motivated by studies reporting the degrading quality of service caused by the overcrowding of the RF spectrum, in particular in unlicensed bands such as the 2.4 GHz band [2]. Several studies have proposed solutions to overcome these interference problems. Chowdhury and Akyildiz identify the type of interferer in order to adapt the resources accordingly and reduce packet losses [18]. Liang et al. increase the resilience of packets challenged by Wi-Fi interference using multi-headers and FEC techniques [8].
Other studies have proposed to hop out of interfered channels dynamically. The ARCH [19] and Chryssos [20] protocols switch the communication frequency when interference is detected. These protocols require algorithms for measuring and quantifying interference and there are several candidates in the literature [4, 15, 21]. On the same line of thought, cognitive radio techniques, which aim at exploiting unused RF spectrum, have been explored in sensor networks [22]. All these studies rely on packet exchanges to coordinate the channel switching and Jam-X can be utilized to improve their performance.

Another set of studies propose to cope with interference by exploiting its idle times. Hauer et al. report the interference observed by a mobile body area network in public spaces, and the study shows the intermittent interference caused by Wi-Fi spots in all IEEE 802.15.4 channels [5]. Similarly, Huang et al. have shown that Wi-Fi traffic inherently leaves “a significant amount of white spaces” between 802.11 frames [23]. Similarly to these studies, Jam-X exploits idle times for data packets, but Jam-X also takes advantage of the bursty non-continuous nature of interference to identify jamming signals that are part of a handshake.

In terms of agreements for broadcast scenarios, there is an interesting set of related studies. SMACK [24] uses simultaneous transmissions from a number of nodes to implement reliable acknowledgements. The nodes use orthogonal frequency division modulation radios (OFDM) to receive packets on different subcarriers simultaneously. These sophisticated radios are able to identify the sender of the message, which is not possible with the single-channel radios implementing 802.15.4. In contrast to SMACK, Pollcast [25] and Countcast [26] approximate the number of senders but they cannot identify individual addresses, which is necessary for an agreement. A study similar in spirit to Jam-X is provided by Krohn et al., where the authors exploit jamming signals for estimating the number of one-hop neighbors [27]. Similar to Countcast, their scheme results in an approximation, which is insufficient to reach agreement.

8. CONCLUSIONS

In this study we propose Jam-X, a simple and efficient agreement protocol for wireless sensor networks working under interference. Jam-X introduces a novel technique that utilizes jamming signals as binary acknowledgements of the reception of a packet. The key insight of our work is a mechanism that permits the reliable detection of intended jamming signals in the presence of different interference patterns. This method overcomes the fundamental limitations of regular acknowledgment packets which often cannot be successfully decoded when interference is present.

We implement Jam-X using Contiki on 802.15.4 platforms and evaluate it with different sources of interference. Our results show that Jam-X outperforms traditional methods using packet-based acknowledgements for both unicast and broadcast scenarios. For a 2-way unicast handshake, Jam-2 sustains 90% and 35% positive agreements under microwave ovens interference and heavy Wi-Fi traffic, respectively. A traditional 2-way handshake (Ack-2), instead, sustains only 60% and 10%, respectively, requiring longer delays and higher power consumption.

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