Abstract

One of the major challenges for the engineering of wireless sensing systems is to improve the software abstractions and frameworks that are available to programmers while ensuring system reliability and efficiency. The distributed systems community have developed a rich set of such abstractions for building dependable distributed systems connected using wired networks, however after 20 years research many of these elude wireless sensor systems. In this paper we present X Process Commit (XPC) an atomic commit protocol framework that utilizes Synchronous Transmission (ST). We also introduce Hybrid, a technique that allows us to exploit the advantages of the Glossy and Chaos Synchronous Transmission primitives to get lower latency and higher reliability than either. Using XPC and Hybrid we demonstrate how to build protocols for the classical 2-phase and 3-phase commit abstractions and evaluate these demonstrating significantly improved performance and reliability than the use of Glossy or Chaos individually as dissemination primitives. We are first to present testbed results that show that Hybrid can provide almost 100% reliability in a network of nodes suffering from various levels of radio interference.

1 Introduction

Wireless Sensor Networks (WSN) are a key technology in environmental and infrastructure monitoring and are giving rise to new solutions across many sectors of industry, including manufacturing, electricity, gas and water supply, construction and agriculture [4][21]. One of the big challenges is to improve the software abstractions and frameworks that are available to programmers to create full-featured WSN that provide system level services like reconfiguration and update, while ensuring efficiency and reliability. This is difficult due to the limited capabilities of sensor nodes as well as the difficulty of overcoming the (often extreme) physical environment impediments that sensors will be presented with potentially causing high rates of both communication and node failure.

The distributed systems community have developed many high-level abstractions for building dependable distributed systems such as for: reliable broadcast, consensus, group membership and view-synchronous communication. The WSN community on the other hand have mostly assumed an asynchronous model and used simpler and less dependable abstractions such as best-effort communication and flooding due to previous difficulties with reliable synchronisation and communication. Yet programmers can benefit from higher-level abstractions, such as the ability to reach agreement, if these abstractions are efficient and reliable. An example application would be to support system reconfiguration like the choice of a new sample rate for sensing applications, perform coordinated in-network processing, [4][14][21] or to make the decision to update to a new software image [16].

Synchronous Transmission (ST) is an important approach where wireless nodes can synchronise and communicate at the same time [13]. Simply put, the physics of synchronous transmission is that if two identical messages arrive at a receiver within 0.5 microseconds then the messages will constructively interfere, and be received correctly. If two messages are different, and arrive within 160 microseconds and have at least a 3dB difference in signal strength, then the stronger signal will be successfully received in spite of the presence of another signal for 2.4GHz radio communication. This is called the capture effect and is the result of non-destructive interference.

Synchronous Transmission allows us to implement abstractions based on the synchronous model for distributed systems, where there is a known upper bound on message transmission and processing time. Glossy and Chaos are two well-known ST examples. Glossy is a reliable, one-to-all, ST communication primitive [10] while Chaos is an unreliable, all-to-all, ST communication primitive [15]. Chaos can terminate much faster than Glossy, but its performance can suffer from network instability and it can fail to terminate in some cases. Therefore a primitive that harnesses the reliability of Glossy with the speed of Chaos can underpin the
abstractions we require.

This paper makes a number of contributions. We present XPC (X Process Commit), a new programming framework for the implementation of atomic commit protocols, and Hybrid, a novel ST approach that uniquely uses the Glossy one-to-all ST primitive and the Chaos all-to-all ST primitive to achieve better reliability and speed than either on their own. To achieve this Hybrid is required to make decisions on the use of the appropriate ST primitive with the best parameters at the time. We provide a detailed evaluation and comparison of Glossy, Chaos, and Hybrid when used for the two-phase commit [12] and three-phase commit [20] protocols. Our results show that in a network of 20 nodes with two sources of high radio interference Hybrid can provide close to 100% reliability when Chaos can not, and latencies that are between 13% - 50% faster than Glossy.

2 Background and Related Work

Wireless sensing systems are difficult to build because of the high rates of failure of both their communication networks and their sensor nodes [7]. Protocols and software abstractions are needed to transform unreliable nodes and links into dependable wireless sensing systems that provide services like network wide updates and in-network processing to support a diverse range of application domains from smart cities to precision agriculture.

2.1 Atomic Commit Protocols

Atomic Commit Protocols [18] are important to all distributed systems that need to maintain a consistent global state across the entire system. Examples for WSN systems might include the uniform rate of sampling for all of the sensors, and the use of the same code version on all of the sensor nodes. Protocols for 2-phase commit (blocking) and 3-phase commit (non-blocking) are the most well established and used to ensure that the nodes in a distributed system agree to commit a transaction.

2.2 Synchronous Transmission

Synchronous Transmission ST communication primitives aim to provide energy and time efficient network-wide broadcasts by synchronously transmitting packets from multiple wireless nodes. They depend upon the radio effects of constructive interference [8], the capture effect [11], or both. Constructive interference occurs when two identical radio messages are received within 0.5 microseconds of each other and can be successfully decoded. The Glossy ST communication primitive [10] was one of the first to use constructive interference, followed by many others [8]. The requirement that both messages are similar makes constructive interference based schemes inherently one-to-many.

The Chaos communication primitive [15] was one of the first examples of the use of the capture effect. The relaxation of the message similarity requirement of constructive interference makes communication primitives using the capture effect all-to-all.

The existence of communication redundancy makes ST communication very reliable in practice. A notable exploration of this property has been the EWSN(Embedded Wireless Systems and Networks conference) Dependability Competition that has been held to assess the reliability of communication primitive, and propose a methodology to assess this [5]. The use of ST protocols is being explored for many high reliability applications [3].

2.3 A²/Synchrotron

Synchrotron [1] is a transmission kernel inspired by Chaos and LWB [9]. It operates in time slots which include the time taken for the reception, processing and transmission of packets. In Chaos, reception rates degrade quickly where there is network interference and link unreliability. Synchrotron addresses this by using time-slotted channel hopping, it spreads transmissions across multiple channels. Each node chooses one channel to use for transmissions within a given time slot. This increases the protocol’s reliability.

A² is a programming library built on top of Synchrotron that provides several higher-level abstractions [1]:

- Disseminate, collect and aggregate. Allows for many-to-one and one-to-many communication.
- Vote. Allows nodes to vote on a coordinator node’s proposal. Voting is best-effort.
- Agreement. 2PC and 3PC for network-wide agreement.
- Group membership. Persistent groups with join and leave capabilities.

Synchrotron suffers from the same scalability and reliability problems as Chaos. Chaos uses a control message that uses a single bit per node in the network to keep track of which nodes have received the latest data. This limits the size of the network that Chaos can be used on.

2.4 Baloo

Although a number of ST communication primitives exist such as one-to-all (Glossy) and all-to-all (Chaos), they are very difficult to program because they rely on the low-level control of timers and radio events. Implementing a network-stack using ST is challenging and time-consuming. Baloo is a middleware layer [13] that addresses this problem. Baloo exposes a well-defined interface to enable the run-time control of ST-primitives by the network layer and makes it possible to create higher level abstractions using ST. It is for these reasons that XPC leverages the abstraction of ST communication provided by Baloo in its design and implementation. It is important to note that Baloo offers a standardised ST layer so that various ST approaches can developed in a comparable way.

In Baloo, the protocol implementation is separated from the lower level manipulation of data packets, data transfers and timing model. The underlying ST primitives (such as Glossy or Chaos) may be changed without affecting the protocols themselves. Higher level protocol logic can then be implemented using callback functions.

Time Division Multiple Access (TDMA) [19] is used by Baloo to create execution rounds and requires a fixed execution time upper time bound for each round. All vital protocol information is sent to the network by a central node on the first slot of each communication round.

Baloo is driven by control packets which are sent by a controller node at the beginning of each round. The packets
contain schedule information (i.e. how to execute the current communication round, and when to wake up for the next round), and configuration information (i.e. slot duration and retransmission count). Nodes that successfully receive and decode control packets can transmit during the subsequent allocated data slots.

While Baloo offers a much needed abstraction layer for ST, it does not offer any services such as those required for voting. In this work we leverage Baloo to provide services to build atomic commit protocols.

3 XPC and Hybrid

In this section we present XPC and Hybrid. XPC is a software library that provides abstractions for the implementation of atomic commit protocols. Hybrid is a way of using both Glossy and Chaos for fast and reliable flooding. The challenge here is to guarantee that the two ST primitives are used at the correct time with the correct parameters to ensure that they complement each other and provide the best of both approaches. This is non-trivial because their timing requirements, message structures and control structures are all different.

3.1 XPC Overview

XPC is designed to create atomic commit protocols such as 2-phase or 3-phase commit for WSN. It makes certain assumptions that are common to sensing applications, like the existence of a global host, although that host does not require more resources than the non-host nodes, which initiates the protocol phases. All of the other nodes act as participants. The XPC global host is in charge of the atomic commit protocol’s overall progress from a network wide point of view. The other nodes either commit or abort a value specified by the global host.

When a new phase begins the XPC global host generates a transmit schedule for the all of the nodes in the network. It sends the schedule in a control packet. Each phase may consist of many rounds, depending on how many nodes respond in the first round. In a network with no interference and good communication links, a phase may only last one round (two in XPC, explained below) if all of the nodes reply in that round. If some nodes do not reply, then a re-transmission round must be scheduled to request communication from only the nodes that did not reply in the first round.

Each schedule must be generated one round in advance. An additional final round is scheduled to handle the potential re-transmissions. Retransmissions to collect lost responses from the nodes can only occur a maximum number of times to ensure that the protocol does not wait forever. This is handled via specific API calls to other layers of the XPC stack.

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Figure 1: Layered overview of all XPC components. XPC lives alongside Baloo’s implementation, processing all communication from the application and managing the commit protocol.

3.3 Baloo Control

XPC uses and configures Baloo in the following ways:

1. Single Initiator. Baloo relies on the presence of a global host. This node is in charge of bootstrapping the network and sending control packets at the beginning of each flood. With XPC, the global host is in charge of the protocol and the protocol state machine.
2. **Retransmissions for Reliability.** WSN links are very unreliable and packets may be lost due to interference or environmental conditions. To mitigate this issue XPC uses retransmissions to execute a phase more than once should there be missing replies.

3. **Additional Final Round.** At the beginning of a Baloo round we cannot be sure whether the XPC global host will receive replies from all of the nodes. If it does not, XPC schedules a “retransmission” round to request information from the hosts that did not reply. XPC schedules a final, empty round to handle the potential for missing replies. In Figure 2 the XPC global host sends control packet C during rounds 1 to N, and expects all of the nodes to reply during their scheduled slots. If all of the nodes successfully reply by round N, a final empty round (denoted as E) is scheduled to communicate protocol termination. If not, another communication schedule will be sent. The empty round was chosen to give the protocol the flexibility to schedule or cancel retransmission rounds dynamically based on the number of nodes that respond.

![Figure 2: Example X-Phase protocol ported to Baloo’s round structure.](image)

In order to support these adjustments, there are a number of common Baloo configurations that will be used by all protocols, regardless of their underlying ST primitive:

- **schedule_period.** All protocols share the same length of time allocated for the execution of the application after a successful iteration of the protocol. This is configured to adapt the protocol to the needs of the top-level application.

- **user_bytes.** All protocol information necessary for a given round is disseminated in a control packet. The host assigns two sections of the optional user_bytes configuration parameter: the first holds the messages sent by the host to all nodes in the network, the second holds the value currently proposed by the host.

XPC is built alongside Baloo and uses its callback structure as seen in Figure 1.

### 3.4 XPC Global Host and Participants

XPC presents an API for stateless primitive manipulation. Protocols that use XPC only have to implement their logic while using on a simplified minimal Baloo callback structure.

In XPC one node is the global host and all other nodes are participants. We present pseudo-code for an XPC initiator node (see Algorithm 1) and an XPC participant node (see Algorithm 2). Within the pseudo-code we denote as parameters to the callback functions all variables present within the global state of the node that will be modified during the execution of the function itself. All variables are passed by reference and updates using the ← operator modify the internal state of the object referenced by the given variable.

#### Algorithm 1: XPC Global Host Pseudocode

1. `function ON_ROUND_FIN(state,mess,retr_cnt,reply_num)
2.   retr_cnt ← retr_cnt + 1
3.   n_slots = XPC_COHORT_NODES - reply_num
4.   if retr_cnt > XPC_TIMEOUT_RETX then
5.     state = XPC_ABORT_STATE
6.   else if reply_num == XPC_COHORT_NODES then
7.     STATE_TRANSITION(state)
8.     n_slots = XPC_COHORT_NODES
9.     retr_cnt ← 0
10.   PREPARE_MESSAGE(state,mess)
11.   Prepare the Control Packet with the mess and n_slots
12. function ON_SLOT_POST(state,mess,reply_num,node_id)
13.   if we have not yet received a reply from node_id while in this state then
14.     PROCESS_MESSAGE(state,mess,reply_num)

The XPC global host (can be the same as the Baloo host) is in charge of the protocol’s progress and therefore determines the contents of the control packets for each round (Algorithm 1). Control packets must always be generated one round in advance. The on_round_finished callback is executed at the end of round t and generates the new control packet which will be sent to initiate round t + 1.

When generating a control packet the global host will first determine how many nodes must be scheduled to reply within the given round (set using n_slots field on line 3). It then determines if it has retransmitted more than the retransmission limit (line 4). If all nodes have replied during the previous round (lines 6-9) the global host updates its state to execute the next protocol phase. It then prepares a control packet with the correct message to send when it reaches the given state (lines 10-11).

All other protocol logic is executed within the on_slot_post callback. The global host processes replies from all of the nodes and determines if the correct nodes have replied and how each reply impacts its state machine. The protocol implemented using XPC will determine state_transition(...), prepare_message(...) and process_message(...).

Participants in an XPC round (see Algorithm 2) will parse the control packet and attempt to execute a state transition based on the new information sent by the host (line 5). Similar to the XPC global host, all participant nodes are allowed to timeout if the information sent by the global host does not cause a change in their state after a set amount of retransmissions (lines 9-10). This is to prevent deadlock. A global host may miss too many replies from a participant and time-out. The current round is aborted and then a new
value is proposed. Due to interference in the network a participant may miss a control packet containing timeout-abort information and may infinitely wait for a specific message from the global host, stalling the whole network for multiple rounds. If a participant reaches an ABORT_STATE due to a timeout it behaves as if it had received a DO_ABORT message. The protocol that is implemented with XPC will determine the state_transition(...) of A.

3.5 Hybrid Synchronous Transmission Scheme

Chaos and Glossy can not be naively combined and be expected to provide low latency and high reliability. We have to determine the appropriate time to use each primitive and what parameters they require.

For Chaos it is important to select the correct slot duration and number of retransmissions. If the Chaos slot duration is too short, few node replies will be received and many retransmissions may be required to receive replies from the remaining nodes. If the initial Chaos slot duration is too long, time may be wasted waiting for replies from nodes.

For Glossy it is important to use it for as few nodes as possible, as each node requires a separate flood.

The Chaos slot duration also has to be bounded in order to fit the TDMA slots of Baloo. The original implementation of Chaos allowed the nodes to communicate until the global host was certain that it had received all of the nodes’ information. In section 4.2 we determined the best Chaos slot duration experimentally for the FlockLab testbed. We leave the question of dynamic slot sizes that adapt to network conditions for future work.

Hybrid organises the use of both Chaos and Glossy. The first transmission of each phase is executed using a Chaos flood with a slot duration selected in order to reach as many node as possible (see Figure 3). If all of the nodes have not responded, then Glossy is then used for reliable retransmissions to collect the remaining information. The use of Chaos first gives us a fast (but unreliable) way to get most of the network. Glossy is then used to get the remaining nodes reliably. Up to a maximum of XPC_TIMEOUT_RETRANSMISSIONS − 1 Glossy floods may be scheduled, after which, if still no reply is heard from every node, the protocol times-out.

Hybrid has to manage the change of packet types used for both Chaos and Glossy, and inform the nodes of the change in ST primitive. It achieves this using the control packet of the XPC global host.

In the remainder of this paper we use XPC to compare Glossy, Chaos, and Hybrid used in atomic commit protocols. Hybrid could be used, in principle, for any application that requires flooding. At the moment, our only implementation of Hybrid is with XPC.

We used XPC to create two reference atomic commit protocols for the purposes of evaluation. We implemented 2-phase commit [12] and 3-phase commit [20] using XPC with Glossy only, with Chaos only, and with Hybrid. These atomic commit protocols are representative of the type of commit protocols that WSN would use to agree upon new sensing parameters or other system configuration.

4 Evaluation

In this section we report experimental results comparing the latency and reliability of Glossy, Chaos and our Hybrid approach. We were not able to evaluate against other ST approaches like Synchotron [1] and Crystal [22] because we were unable to get the code to work reliably, a well documented issue highlighted by other researchers, however we compare our figures with published Synchotron values running in the same testbed.

We used XPC to create two reference atomic commit protocols for the purposes of evaluation. We implemented 2-phase commit(2PC) [12] and 3-phase commit(3PC) [20] using XPC with Glossy only, with Chaos only, and with Hybrid. These atomic commit protocols are representative of the type of commit protocols that WSN would use to agree upon new sensing parameters or systems configurations. We evaluate the agreement outcome and the latency of each of the atomic commit protocol with each ST primitive. The we experimentally evaluate the robustness of the atomic commit protocols with different degrees of radio interference. Finally, we compare our latency results to the reported results of A²/Synchotron which uses Chaos [1].

Our analysis was performed using 22 and 27 TelosB nodes(depending on availability at the time) on the FlockLab testbed [17]. FlockLab has resources to monitor the low-level execution of the nodes that is mentioned in section 5.2 and has been one the main testbeds used in ST research. Given the inherent scale limitations of both Glossy and Chaos (scale is an open problem in ST research), we believe that the FlockLab testbed provides an adequate network

| Function | Parameters | Description |
|---------------------------------|------------|-------------|
| function ON_CTRL_SLOT_POST(state, ctrl, mess, retr_cnt) | state, ctrl, mess, retr_cnt | Send the node’s turn to transmit if retr_cnt > XPC_TIMEOUT RETX then state = XPC_ABORT_STATE if state == XPC_ABORT_STATE then mess = XPC_DO_ABORT prev_state = state STATE_TRANSITION(state, ctrl, mess) if prev_state != state then retr_cnt ← 0 if it is node_id’s turn to transmit then Send the mess using the correct primitive

Figure 3: Overview of Hybrid execution across multiple phases. Each phase starts with a Chaos dissemination round, followed by a variable number of Glossy floods.
size and network density for our evaluation.

4.1 XPC using Glossy

XPC with Glossy uses a time-sliced data dissemination approach. Given a network of $k$ nodes (where one is the XPC global host), each round a $\text{schedule.n_slots}$ field is set to $k-1$. All nodes, except the global host, communicate in a given $\text{schedule.slot}$ (see Figure 4a). The nodes receive round information from the global host within the control packet. Nodes reply to the host by broadcasting during their scheduled slot. The payload exchanged during each round contains the messages sent by each node as a reply to the host. When XPC uses Glossy, each reply is one byte.

The Glossy-based protocols keep track of nodes that do not reply in their scheduled slots and schedule them to retransmit in the subsequent round during the same phase.

4.1.1 Two-Phase Commit with Glossy

Our first set of results show that 2PC is unable to reliably reach all nodes in one round while the introduction of re-transmission rounds greatly boosts the overall reliability (Figure 5a). Note that there are very few timeout aborts when retransmissions are used.

The results in Figure 5b show that retransmissions do not significantly increase the latency of the protocol. With no retransmissions the protocol reaches a timeout abort in approximately 30% of the runs.

4.1.2 Three-Phase Commit with Glossy

The results in Figure 5c show that “timeout commits” do not change the reliability of 3PC-Glossy when compared to 2PC-Glossy (Figure 5a). The most significant affect can be seen in latency (Figure 5a). 3PC has one more phase, and a higher latency when compared to 2PC.

4.2 XPC using Chaos

Compared to Glossy, Chaos prioritises latency over reliability. As can be seen in Figure 6 Chaos floods occur in a “best-effort” fashion. There is no certainty that a round will

be long enough for communication to reach all of nodes in the network and aggregate their replies.

The slot duration is the most important parameter when using Chaos with 2PC and 3PC. Chaos floods are hard to time bound, they were originally designed to last until all of the nodes cease to receive new information from their neighbours. With XPC the challenge is to bound the maximum communication time of a Chaos flood, the slot duration. Another challenge is that Chaos is unable to directly target a specific node in the network when requesting retransmissions due to missing replies. It is also unaware of how many iterations will be required for the missing packets to reach the host. XPC schedules a new round of the same length using the payload of the previous round (Figure 6). Communication ceases when no node sees new information in the packets being broadcast (as seen in Figure 6). The Chaos flood is resumed exactly from where it was last stopped by XPC, and it is given extra time so that it will terminate.

In our experiments with 2PC-Chaos and 3PC-Chaos we explore two parameters: the number of retransmissions and the Chaos slot duration. The results in Figure 7 validated our assumptions: a longer slot duration (i.e. 100ms or 200ms) reliably achieve near 100% reliability, very similarly to XPC using only Glossy.

4.2.1 Two-Phase Commit with Chaos

The results show very poor reliability for 25ms slots (Figure 7a) with improved results for 50ms slots (Figure 7b). For latency, the results show that 25ms slots (Figure 7a) have higher latency than 50ms slots (Figure 7b). For Phase 1, 2 retransmissions for Phase 2, and a final retransmission to communicate the end of the 2PC round. The protocol uses 2 rounds for each communication phase. This is an indication of a communication slot that is too short in duration. Not all nodes are reached, and multiple retransmissions are required.

We analysed the cause for this unreliability using FlockLab GPIO (General Purpose Input/Output pins, in this case used as LED lights) traces. On the FlockLab testbed the red LED is set when the radio is turned on, the purple LED is set upon the reception of a radio message, and the yellow LED is set when a radio message is broadcast. The setting of an LED has little time overhead when compared to writing output to serial. FlockLab offers a web visualiser for GPIO outputs. All of the logs have matching timestamps across the various nodes in the network.

We analysed a GPIO pin trace of 2PC-Chaos with 25ms slots and 1 retransmission because it was unable to commit without retransmissions (Figure 7a). Most of the executions present in the GPIO traces aborted with a time-out due to missing replies. Figure 7a a representation of a successful commit that required 5 retransmissions: 2 retransmissions for Phase 1, 2 retransmissions for Phase 2, and a final retransmission to communicate the end of the 2PC round. The protocol uses 2 rounds for each communication phase. This is an indication of a communication slot that is too short in duration. Not all nodes are reached, and multiple retransmissions are required.

The FlockLab GPIO trace for a 50ms slot duration was very different. Most of the executions in the traces were successful. The Figure 8a shows a representation of a successful commit execution with 3 rounds.

The issue is that Chaos needs gap times for its callback functions. If the slot duration is short, the next round occurs before the end of the gap times. We see that a 100ms slot
The results for 100ms and 200ms slots in Figure 8 show that 2PC-Chaos can be reliable and have a lower latency than 2PC-Glossy. Above 95%, reliability is achieved with 100ms long Chaos floods and 325ms latency. Close to 100% reliability can obtained with 200ms floods with a latency of 525ms, around 40% less than 2PC-Glossy when run on FlockLab. With longer Chaos flood durations the number of retransmission numbers does not greatly increase the overall latency. The protocol has a high reliability from the first transmission slot.

4.2.2 Three-Phase Commit with Chaos

The results show that 3PC-Chaos suffers from the same reliability and latency concerns as 3PC-Glossy. The reliability of 3PC-Chaos (Figure 10) is worse than 2PC-Chaos. This is due to the addition of an extra Chaos round and the “time-out commit” that is a part of 3PC. Similar to 2PC-Chaos, above 90% reliability can be achieved with 200ms transmission slots.

3PC-Chaos latency increases with the introduction of an additional communication round, but remain lower than 3PC-Glossy (Figure 11). Chaos is a fast ST primitive with a low overall protocol execution time. Unfortunately, Chaos can be unreliable on low-power multi-hop networks.

4.3 XPC using Hybrid

In this section we evaluate XPC that harnesses both Chaos and Glossy into the same protocol solving the latency issues of Glossy and the reliability issues of Chaos.

When utilising ST primitives it is very important to select the correct Chaos slot duration and number of retransmissions. If the Chaos slot duration is too short, few node replies will be received and many Glossy rounds will be required. If the initial Chaos slot duration is too long, time may be wasted waiting for replies from nodes.

4.3.1 Hybrid Two-Phase Commit

Our results for 2PC-Hybrid use the same Chaos slot duration used for the evaluation of Chaos on its own. The slot duration only determines the length of the first round of each protocol phase. The subsequent retransmissions use Glossy. We can see in Figure 12 that the Glossy retransmissions increase the protocol reliability to 100% for our experimental set-up. The latency (Figure 13) is also very close to that of 2PC-Chaos.

4.3.2 Hybrid Three-Phase Commit

The results for 3PC-Hybrid (Figure 14) show that agreement can be reached reliably with 4 or 5 retransmissions for any slot duration. A 100ms slot duration can reach 100% reliability with 3 retransmissions. At 200ms high reliability can be achieved with no retransmissions.

The latency of 3PC-Hybrid (see Figure 15) is very close to that of 3PC-Chaos. Our data shows that XPC using Hybrid to schedule ST primitives can be used to realise higher-level abstractions for use in synchronous WSNs with good performance and reliability.

4.4 Interference Analysis

We focus our next set of experiments on the reliability of our Hybrid under varying amounts of radio interference. Interference causes nodes to miss broadcasted packets, and potentially desynchronise from the network (causing transmission slots to be missed); protocol reliability must therefore be analysed in the presence of network interference.

Our previous experiments were done during times of low radio interference, i.e. in good conditions. We established that Hybrid out-performs both Glossy and Chaos in such conditions. In the next set of experiments we evaluate Chaos, Glossy and Hybrid with much greater radio interference.

The experiments were performed on the Flocklab testbed. Of the 22 functioning node, we choose between 1 and 8...
nodes to inject interference into the network. We increase the interference by using different interference models, and different numbers of interfering nodes. The interfering nodes were \{31, 20, 27, 28, 8, 6, 4, 3\}. These interfering nodes were selected as nodes that are physically close enough to another node to be able to jam its radio reception. The jamming nodes use JamLab [6], a customizable off-the-shelf radio interference generation library for WSN motes. JamLab
Figure 11: Latency of XPC 3PC-Chaos with varying slot duration in FlockLab.

Figure 12: Agreement outcome of XPC 2PC-Hybrid with varying slot duration in FlockLab.

Figure 13: Latency of XPC 2PC-Hybrid with varying slot duration in FlockLab.

Figure 14: Agreement outcome of XPC 3PC-Hybrid with varying slot duration in FlockLab.
provides a set of interference profiles (explained below), that are becoming an accepted way to evaluate WSN protocols in comparable conditions. The following interference patterns (as discussed in [6]) were used to perform comparisons:

1. **Low Interference** is determined by background noise on the FlockLab testbed during night-time hours (9pm-6am). This models an ideal network deployment.

2. **High Interference** is determined by background noise on the FlockLab testbed during day-time hours (7am-8pm). It provides an estimate of average real-world conditions.

3. **WiFi Interference** is generated by JamLab and emulates the interference of non-saturated WiFi file transfers and radio streaming.

4. **Microwave Interference** is generated by JamLab and emulates the periodic interference caused by microwave ovens over 802.15.4 transmission channels. All nodes in the network vote in favour of all proposed values (100% agreement rate) and each protocol phase is allowed up to 9 retransmissions before timing out and aborting. The Chaos slot duration for Chaos and Hybrid is 50ms. The interference experiments were run on Flocklab at a time when 22 node were functional.

It is important to note that we consider WiFi and Microwave interference to both represent a high degree of radio interference. Both types of JamLab injected interference (WiFi and Microwave) were executed during night-time hours to minimise other external interference. Our FlockLab interference analysis uses the following:

- **Interference Model.** Low, High, WiFi and Microwave interference models were tested and evaluated individually for each protocol.

- **Average Reliability.** Protocol reliability measures the rate at which all nodes in the network commit the proposed transaction consistently. If even just one node times out or aborts, the reliability is scored as zero for the given round.

- **Latency.** Latency measures the overall time from the beginning of an XPC transaction (i.e. when the Application layer is pre-empted) until the application is resumed at the end of the XPC round. Protocol latency is expected to increase with the interference.

- **First Round Coverage.** The First Round Coverage metric expresses the percentage of network nodes reached, on average, during the first dissemination of each phase, which are denoted as P1, P2 and P3 depending on the number of phases.

- **Average Number of retransmissions.** This metric expresses the average number of retransmissions required for a protocol to switch to a subsequent stage.

### 4.5 Single Jammer

The results of 2PC-Glossy, 2PC-Chaos, 2PC-Hybrid and 3PC-Hybrid, evaluated under the four interference models outlined above can be seen in Table 1. The Table presents the interference caused by one node with a variety of different interference patterns.

An interesting result is the poor latency and reliability of 2PC-Chaos across all experiments under these harsher (but realistic) conditions. This result is not surprising, and has been observed by others using Chaos based protocols [2]. A point needs to be made about the difference in latency results for Chaos in these experiments when compared to Figure 8. Here we measure the overall latency of both committed and aborted (due to timeout) transactions. In Figure 8 we only measure the latency of the commit transactions. This shows us the potential benefits of combining Chaos and Glossy in real world end-to-end execution a system in the presence of interference.

We make the following further observations about the data presented in Table 1:

- **Reliability.** The protocols aside from Chaos across all interference models achieve a 100% correct outcome. This data shows the high reliability and low latency of Hybrid. Not only is the correct functionality of the protocols maintained in ideal (Low Interference) and normal (High Interference) network conditions, but it is also resilient to network interference injected to cause packet loss and broadcast conflicts.

- **Latency.** As the interference models increase their disturbance over the channel, protocol latency’s increase linearly. The stronger WiFi and Microwave radio inter-
ference causes longer latency for 3PC-Hybrid.

- **Chaos Coverage.** In spite of the problems with Chaos when used on its own, when combined with Glossy into Hybrid it works very well. Being able to reach over 90% of nodes during the first 50ms of each phase reduces latency; subsequently switching to reliable Glossy broadcasts is then able to compromise for Chaos’ unpredictable termination time and lack of reliable detection of straggler nodes.

- **Average retransmissions.** Similar to the analysis with latency and Chaos round coverage, the average number of phase retransmissions reflects the intensity of the channel’s interference. As the interference increases all of the protocols require more retransmissions to maintain reliability.

4.6 Multiple Jammers

We extend our analysis to consider the impact of increased interference in the network. The purpose of this evaluation is to disrupt the network in degrees until we can see complete failure. We do this using multiple nodes generating jamming interference in the network. We select the microwave oven as an extreme form of interference By increasing the number nodes generating microwave oven interference we create a more challenging communication environment for the evaluation of the robustness of the protocol. It is important to note that all of the degrees of interference represented in this experiment are high. We consider that beyond three jamming nodes represents extreme interference that is beyond what would be expected of a normal operational environment. Table 2 reports the results of executions with between 2 and 8 interfering nodes.

The results in Table 2 show that 2PC-Hybrid is faster than 2PC-Glossy for small amounts of interference. At one to two interfering nodes 2PC-Glossy has higher latency than 2PC-Hybrid because it does not have the initial Chaos flood used by Hybrid to efficiently flood the network with data. We can see that the first transmission coverage is higher and the average retransmissions are lower for Glossy, but the latency is higher.

At three interfering nodes the reliability of 2PC-Glossy and 2PC-Hybrid begin to degrade. We still see very similar reliability for both. At this point the initial Chaos round reaches fewer nodes and both protocols rely on Glossy floods. With four interfering nodes 2PC-Glossy is more reliable than 2PC-Hybrid. This occurs because both are now reliant upon Glossy, and 2PC-Glossy has 10 glossy retransmissions while 2PC-Hybrid has 9 glossy retransmissions. This trend continues as the number of interfering nodes increases. With six interfering nodes the protocols have essentially failed. None have a reliability above 10%.

The unreliability of Chaos rounds are clearly seen with the performance of 2PC-Chaos. At four interfering nodes 2PC-Chaos has completely failed. We also see that Chaos has a very high count of average retransmissions.

3PC-Hybrid behaves similarly to 2PC-Hybrid, with a 50% extra latency due to the extra phase. From the experiment traces we can see that the 1st dissemination phase usually has the highest retransmissions. This is probably caused by nodes finding it harder to capture the control packet for the next round while under interference. At 8 jamming nodes we note that 3PC-Hybrid completely fails to receive any packets for the first Chaos transmit of the second and third phases. We also see the total number of retransmissions at their maximum value.

5 Limitations and Further Work

The limitations of this work are typical of those in this field. It is difficult to control the radio environment of a remote WSN testbed. We hold that our best-effort experiments with the injection of radio interference do tell us something useful about the resilience of the hybrid use of Glossy and Chaos. A more controlled environment could have given us more precise results.

Hybrid also suffers from the same issues of scale shared by Glossy and Chaos. Glossy needs an individual network-wide flood for each node. Chaos uses a control frame that contains one bit for each node in the network. Both of these limit the size of network that each can be used on.

We are developing this work as part of a large smart city wide deployment of sensors in (name hidden for double blind review) to support the management of lifts, waste pipelines and pollution monitoring applications. This will enable both parameter updates and code updates as a result. For further work, we would also like to extend the use of XPC and the Hybrid ST approach to see what further communication pro-


| Jamming Nodes | Reliability (%) | Latency (ms) | 1st Tx Coverage (%) | Avg. Ret.|  
|---------------|-----------------|--------------|---------------------|---------|
| 2 Jamming Nodes | | | | |  
| Glossy | 100.00 | 593.33 | 1st Tx Coverage | 1.29 |
| | 355.11 | | Avg. Ret. | 2.12 |
| 2PC | 94.34 | 56.32 | | 1.37 |
| 3PC | 95.00 | 48.93 | | 1.43 |
| Hybrid | 97.79 | 42.86 | | 1.49 |
| Multijamming | 10.00 | 84.66 | | 1.56 |
| 3 Jamming Nodes | | | | |  
| Glossy | 100.00 | 787.45 | | 1.56 |
| | 84.66 | 1480.84 | | 1.63 |
| 2PC | 94.14 | 969.45 | | 1.66 |
| 3PC | 95.00 | 841.74 | | 1.71 |
| Hybrid | 97.97 | 720.12 | | 1.76 |

Table 2: Comparisons of XPC protocols with multiple jamming nodes (Microwave Interference).

6 Conclusion

In this paper we present X Phase Commit(XPC) for the implementation of atomic commit protocols using Synchronous Transmissions, and Hybrid. We describe the design of XPC and reference implementations of two-phase commit and three-phase commit using two of the most common ST primitives, Glossy and Chaos. We also present Hybrid, a way to use both Glossy and Chaos to provide fast and reliable flooding. We used XPC and our reference implementations to assess the latency and reliability of Glossy, Chaos, and Hybrid for both the two-phase commit and three-phase commit transactional protocols.

Our testbed evaluation showed that Hybrid enabled by XPC has a lower latency than Glossy on its own, and is more reliable than Chaos on its own. We evaluate evaluated Glossy, Chaos, and Hybrid with increasing levels of network radio interference and saw that under low to moderate interference Hybrid was as reliable as Glossy but with a lower latency. The XPC library is available online at GITLAB.

7 References

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tocols could be supported, or what new ones could be developed. We would also like to explore a way to incorporate the use of multiple channels to increase resilience.
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