eXtend Collection Tree Protocol

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***Abstract*—In this work, we propose eXtend Collection Tree Protocol (XCTP), a routing protocol that is an extension of the Collection Tree Protocol (CTP). CTP is the de-facto standard collection routing protocol for Wireless Sensor Network (WSN). CTP creates a routing tree to transfer data from one or more sensors to a root (sink) node. But, CTP does not create the reverse path between the root node and sensors nodes. This reverse path is important, for example, for feedback commands or acknowledgment packets. XCTP enables communication in both ways: root to node and node to root. XCTP accomplishes this task by exploring the CTP control plane packets. XCTP requires low storage states and very low additional overhead in packets. With the reverse path, it is possible to implement reliable transport layer protocols for Wireless Sensor Network (WSN). Thus, we designed Transport Automatic Piggyback Protocol (TAP2), a transport protocol with Automatic Repeat-reQuest (ARQ) error-control on top of XCTP. We implemented these protocols on TinyOS and evaluated on TOSSIM. We compared XCTP with CTP, Routing Protocol for low-power and lossy networks (RPL), and Ad hoc On Demand Distance Vector (AODV) protocols. We conducted scalability and stress tests, evaluating them with different loads and number of nodes. Our results shows that XCTP is more reliable then CTP, delivering 100% of the packets. XCTP sends fewer control packets than RPL. XCTP is faster to recovery from network failures and also stores fewer states than AODV, thus being efficient and agile.**

I. Introduction

Wireless Sensor Networks (WSNs) are composed of a large number of nodes with sensing, computation, and wireless communication capability. These networks have computing and communication energy constraints. Many applications in WSN need to transport large amount of data (image, audio, video monitoring). These applications are not tolerant to data loss, thus it is important to provide mechanisms to reliable collect data.

The WSNs have the following communication paradigms: *many-to-one* (data collection), *one-to-many* (data dissemination), and a more complex way that enables communication *any-to-any*. First two paradigms allow the collection and dissemination of data respectively. However, with routing on only one direction, it is infeasible to build reliable mechanisms to ensure the delivery of data end-to-end. *Any-to-any* communication paradigm allows communication between any pair of nodes in the network, but adds more complexity and also requires large amounts of memory to store all possible routes.

In this work, we present eXtend Collection Tree Protocol (XCTP), a routing protocol that is an extension of the Collection Tree Protocol (CTP). CTP creates a routing tree to transfer data from one or more sensors nodes to a root (sink) node. But, CTP does not create the reverse path between the root node and sensors. This reverse path is important, for example, for feedback commands or acknowledgment packets. XCTP enables communication in both ways: root to node and node to root. XCTP requires low storage of states and very low additional overhead in packets.

Our main contribution are as follows:

- We propose eXtend Collection Tree Protocol (XCTP), which allows routing of messages in the reverse direction of CTP, using a few extra memory to store reverse routes.
- We compare the performance of XCTP, Ad hoc On Demand Distance Vector (AODV), Routing Protocol for low-power and lossy networks (RPL), and CTP. In the experiments, XCTP proved to be more reliable, efficient, agile, and robust.
- We show that it is possible to implement reliable data transport protocol over XCTP.

CTP optimizes data traffic towards the root thus achieves high packet delivery rate. However, our XCTP approach goes beyond, allowing bi-directional communication between sensor nodes and the root. XCTP and *any-to-any* routing protocols enable reliable communication. However, XCTP reduces the cost to store routes, since XCTP does not need to maintain routes to every peer.

Our work is organized as follows. In the next section, we present some works related to XCTP. In Section III, we formally define the problem being solved in this work. We describe XCTP architecture in Section IV. We compare XCTP with AODV, RPL, CTP, and present the simulation results in Section V. Finally, we conclude in Section VI.

II. Related Work

Table I. Comparison of communication paradigms.

One-to-Many (Dissemination)	Many-to-One (Collection)		Any-to-Any (P2P)
Unreliable	***Unreliable***	***Reliable***	***Reliable***
Directed Diffusion [1]	CTP [2]	**XCTP**	AODV [3], DYMO [4]
(DIP, DRIP, DHV) [5]	MultiHopLQI [6]		DSR [7], Hydro [8]
Deluge [9]	MintRoute [10]		RPL [11]

We present in Table I the main related protocols. We classified them according to the communication paradigm (*any-to-any*, *many-to-one*, *one-to-many*). Table I shows that XCTP is, to the best of our knowledge, the only Reliable Collection protocol. In other words, it is a data collection protocol that also allows unicast routes root-to-node. Besides that, it offers an interface that facilitates the development of reliable end-to-end transport protocols.

From the protocols presented in Table I, Directed Diffusion [1], (DIP, DRIP, DHV) [5] are used for dissemination of small data packets in the network. DIP, DRIP, DHV offers eventual consistency models and use timers based on Trickle [12]. DRIP treats each information as a separated entity, which allows more control of when and how fast the data will be disseminated. DIP and DHV treat data as a group, meaning that control and dissemination parameters are applied equally for all data.

CTP and Deluge are related protocols. CTP is a data collection protocol that uses Expected Transmissions (ETX) metric to estimate the link quality and route cost. Data and control packets are used to obtain the link quality. XCTP is an extension of the CTP. Besides creating unicast routes to a data collection point, XCTP also creates unicast routes from the root to the sensors. Deluge is a protocol that operates under the *one-to-many* paradigm, which has the objective to propagate large amount of data, as is the case, when reprogramming the network nodes.

Hydro [8] and RPL [11] are protocols that aim at maintaining any-to-any communication in WSN. Hydro differs from our approach, which focus in creating unicast routes to exchange messages in both directions root-to-node and vice-versa. Routing Protocol for low-power and lossy networks (RPL) disseminates Destination Advertisement Object (DAO) messages to announce routes for each destination. While RPL requires control packets to create downward routes, XCTP does not have this overhead since XCTP takes advantage of the data packets. XCTP also allows non utilized downward routes to be removed through TTL-based policy, avoiding memory overhead to store states with peer-to-peer routes that are under-utilized in WSN.

AODV [3] and Dynamic Source Routing (DSR) [7] are on-demand routing protocols for any-to-any communication. AODV floods the network with messages RREQ to build a path till the destination. On the other hand, DSR protocol uses the packet header to store the route path. Unlike DSR, our protocol does not store any routing information in the packet header. AODV protocol has some similarity with XCTP in the strategy of storing the reverse path. However XCTP, unlike AODV, does not save routes that are not reverse among the sensor nodes and the base station. Dymo [4] is the AODV successor, however it is optimized for MANETs.

None of the protocols here related allow sending unicast messages in *root-to-node* direction and vice versa, except those *any-to-any* protocols that require large amount of information to be stored or control messages.

III. PROBLEM

The data delivery reliability is one of the most challenging problems in WSN, due to frequent link instability in fractions of a seconds, many times in less than $1s$ [13]. Therefore, it brings basic requirements that are fundamental for any routing protocol for low-power and lossy networks (L2Ns): 1) **reliability**, it should deliver the largest possible amount of packets, when there is route between the participants communication; 2) **robustness**, the protocol should operate in different topologies, loads, amount of sensor nodes and in the presence of failures; 3) **efficiency**, the protocol must deliver packets with the least amount of transmissions, save energy and keep the least amount of possible states.

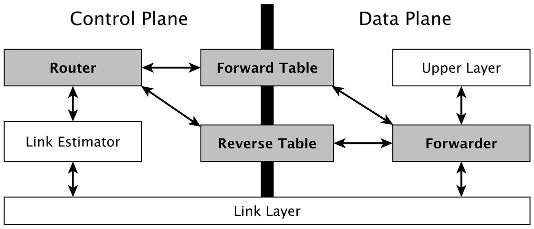


Figure 1. XCTP architecture.

An alternative to collecting data in a reliable, robust and efficiently mode is using XCTP. This protocol balances the compromises imposed by the three fundamental goals of WSN. XCTP adjusts the communication model for data collection to provide routes that enable feedback commands, confirmation messages or control messages to be exchanged in bi-directional form between any sensor node and the base station. XCTP allows data transport protocols with confirmation be built. Thus, XCTP enables reliable data deliver.

IV. SOLUTION

A. XCTP Architecture

Here, we describe XCTP architecture. To accomplish the task of forwarding packets also in the reverse direction of the standard CTP data flow, we had to modify CTP architecture by adding new features to the protocol rules as well as incrementing the packet format. We did a minor modification in the data packet by adding a new field. We also created a reverse flow table. The protocol rules were modified at the control and data planes. The data plane was changed to query the reverse flow table. The control plane is responsible for the construction and modification of this table. The control plane was modified to manipulate the reverse fluxes and also to react appropriately to the two main events:

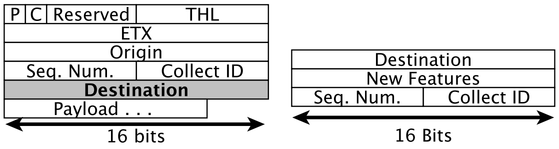
1) **Reverse flow:** correct and efficient installation of the reverse flow rules;
2) **Topological changes**: nodes must appropriately react when loops occur or when CTP unicast routes change.

In Figure 1, we show the relationships between modules. Major changes are highlighted in gray. The Router module is responsible for filling the Forward and Reverse tables. These tables indicate what is the next hop for the data packet to be transmitted. We did not modify the Link Estimator module. This module estimates the quality of the links to the neighboring nodes. The quality of the links are estimated using beacons and data packets. The Forward module queries the Forward and Reverse tables, and determines any router inconsistencies to inform the Router module. It also keeps a packet queue for transmission and check for duplicate packets. The Link Layer module contains the features used in radio communication. Finally, the Upper Layer module is the interface provided to implement components that utilizes XCTP.

B. Changes in data packet

To allow the navigation of the reverse data packet, we added a 16 bits packet field to the data packet to represent the address of the message destination. Figure 2(a) shows the new data packet format. The packet fields are: *P* allows node to request routing information to other nodes; *C* indicates congestion notification; *Time Has Live (THL)* each node, when receiving a packet, increments this field; *ETX* routing metric for routes construction and loop detection; *origin* address of the source node; *destination* address of the destination node; *seq. num.* sequence number; *collect ID* collection tree identifier; *Payload* packet data content.

We also created an Acknowledgment (ACK) packet. The ACK packet has a subset of the data packet fields, as illustrated in Figure 2(b). The *New Features* field 16 bits is reserved for future features. The ACK packet is useful as feedback message for end-to-end transport layer implemented over XCTP.



(a) Data packet with new destination address field.

(b) Acknowledgment Packet.

Figure 2. Packet formats for XCTP protocol.

C. Reverse Flow

The control plane is responsible for the manipulation of the XCTP reverse table. The reverse table has the following fields: *addr dest*: XCTP tree descendant (but not 1-hop neighbor); *next hop*: neighbor address to reach destination; *TTL*: route time to live, where we can apply removing policies. The Router module implements the basic operations Creation, Read, Update, and Delete over the reverse table.

1) Creation: The table starts empty. When a sensor node forwards a message to the root, the reverse route is installed. Since the link estimator module stores information about the 1-hop node neighbors, the router module does not insert entries in the reverse table of 1-hop neighbors. Figure 3(a) illustrates this situation: where node C sends data to the root, the intermediate node (that is not a 1-hop neighbor of C) intercepts the packet from source C and install a reverse flow.

2) Read: Router module provides an interface to query the table. This mechanism is used for data and control planes. In Section IV-E, we provide details of using this interface.

3) Update e Delete: Router module provides mechanisms for updating and removing installed rules. These functions are called when there is a topology change (see Section IV-D).

There is a trade-off between agility and efficiency regarding the maintenance of routes in L2Ns. Agility refers to how fast the network can react to a topological change, while efficiency is the energy consumption and the number of packets sent to keep the network operational. The network requires high frequency of the beacons to keep routes updated. This increases the agility of the network but, on the the hand, it reduces efficiency. CTP uses the Trickle algorithm [12] to increase the number of beacons when the network is unstable and exponentially reduces the number of beacons when the network is stable, thus keeping a trade-off balance between speed and efficiency. XCTP uses the data packets to create the reverse route, thus, there is no need for extra beacons.

Algorithm 1 Internal operation sendTo() interface.

```
if $isDataXCTP(pkt)$ $or$ $isAckXCTP(pkt)$ then
    if $pkt.destination = my.addr$ then
        // Process package locally.
    else if $pkt.nextHop = nextHop(pkt.dest)$ then
        // Send unicast message to neighbor in reverse flow.
    else
        // Drop pkt or forwards to the base station.
    end if
else
    // Normally forwards packets through tree XCTP.
    pkt.nextHop = nexHop()
    forward(pkt)
end if
```

D. Topology Changes

A routing system must know when and where to change the reverse routes of the data plane so it can correctly react to the network topology dynamics. XCTP control plane reacts and changes the data plane for reverse routes when there is the occurrence of loops or link failures.

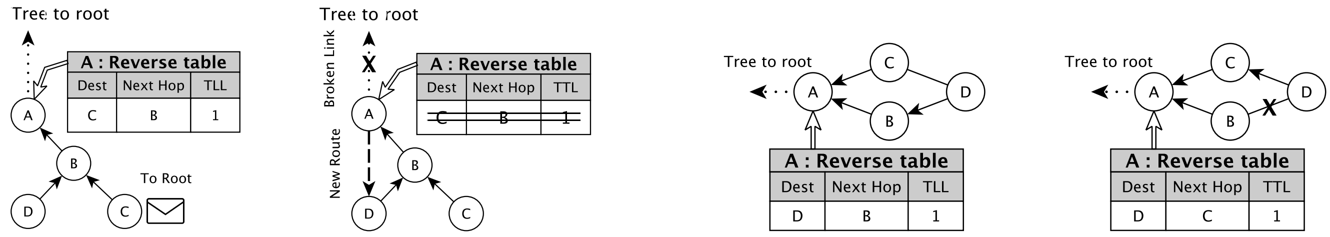
To maintain the consistency of routes, each sensor node keeps the estimated route cost to the base station. Moreover, this information is attached to the control and data packets (see Figure 2(a)). XCTP uses ETX as the metric cost. The route cost is always increasing towards the leaf nodes of the routing tree and this invariant must always be maintained. Loops are detected when this invariant is broken. In this case, the reverse flow table entry is removed.

Figures 3(a) and 3(b) illustrate this situation. In Figure 3(a), we show the initial flow table. Then, as shown in Figure 3(b), there is a link failure which causes a loop between nodes A, B, and D. In the event of a loop, the data plane marks, in the reverse flow table, the sensor nodes that were descendants and now are parents in the routing tree. Therefore, the action taken when loops are detected by XCTP data plane is to signal the control plane for the loop detection so that the appropriate reverse flow table entries are cleared. The reverse flow entries are reconstructed when there are new data packets in the network.

In case of link exchanges due to the dynamics of link quality, the control plane must update the data plane reverse flow entries to reflect this new routing tree configuration. The reverse flow table is updated when a data packet from an already installed flow is intercepted but it was routed through a different neighbor. Figures 3(c) and 3(d) illustrate this case. Data packets from node D towards the root was forwarded by node B and changed to be forwarded by node C due to changes in link quality. Thus, the data plane of node A must be updated to reflect this new configuration: the reverse flow should be forwarded by node C.

E. API

Here, we describe the XCTP Application Programming Interface (API). The CTP protocol does not require a destination address. XCTP, on the other hand, needs a destination address to provide unicast routing to a specific sensor node. XCTP integrates an interface that includes the destination address



(a) XCTP routing tree with reverse flow table.

(b) Reverse flow table is outdated due to routing loop.

(c) Reverse flow table before link update.

(d) Updating reverse flow rule.

Figure 3. Control plane reactions over the data plane rules when detecting a routing loop and updating the routing paths.

as well as routines for handling and the reverse and forward tables. The routines are:

- **addr sendTo(target, pkt):** where *target* is the destination address of XCTP *pkt* packet.
- **addr nextHop(target):** where *target* is an optional parameter. If *target* is instantiated, nextHop(target) routine queries the Reverse Table, otherwise the message is towards the base station.
- **loopDetect():** this routine signals the control plane when a loop is detected (see Section IV-D).
- **snoopNewPkt(pkt):** when intercepting a data packet from a new flow, the control plane must signal to update the reverse and forward tables.

Thus, the interface *sendTo(idNode,pkt)* should be used when the base station needs to send a packet to a specific node.

Algorithm 1 describes this routine. On line 1, we check if it is a data or acknowledgment packet because only these two packet types should travel on the reverse path. Then, the destination address is extracted. If the destination is the node itself (line 2), the packet has reached its destination and it should be properly processed. If the destination is one of its descendants (line 4), the packet is forwarded. Otherwise the recipient is not in any of the routing tables. In this case, there are two approaches: discard the packet or forward the packet to the base station (line 7). In the second case, since the root knows the entire network topology, the root can forward the packet or just discard it. If the packet does not have a valid address, XCTP routes the messages directly to the root (lines 10-12).

XCTP permits the any-to-any communication paradigm. This is possible due to how the the reverse route is constructed (line 7 of Algorithm 1). If a node X wants to directly connected to a node Y, node X can use the routine *sendTo(Y, pkt)*. Node Y will receive the message from an ancestral of node X or, in the worst case, the message will go to the root and towards node Y.

F. Transport layer over XCTP

Using XCTP API, we implemented a reliable transport protocol, called Transport Automatic Piggyback Protocol (TAP2). TAP2 uses piggyback and Automatic Repeat-reQuest (ARQ) error-control mechanism for packet retransmission. Other transport protocols for WSN such as [14], [15], [16] can also be implemented over XCTP. However, the requirement of a few computing resources and its simplistic implementation were reasons why we chose this approach in our work.

V. Evaluation

In this section we analyze XCTP and compare it with three protocols: CTP, RPL, and AODV. The objective of this analysis is to show that the protocol is working properly, as well as to evaluate XCTP performance when compared with the current state-of-the-art protocols. We analyzed according to the following items: 1) favoring the construction of data transport protocols; 2) robustness in the presence of faults in different topologies; 3) scalability. 4) control traffic.

A. Simulation

Of the protocols shown in Table I, Directed Diffusion [1], Deluge [9], (DIP, DRIP, DHV) [5] are used just for data dissemination in the network and do not serve to compared with XCTP. Collection Tree Protocol (CTP) [2] is one of the newest protocols and it presents better results than MultiHopLQI [6] and MintRoute [10] in data collection. To the best of our knowledge, there are no stable and open source implementations to the community of Dymo [4], DSR [7] and Hydro [8]. Therefore, we made comparisons with RPL [11], AODV [3], and CTP.

XCTP, CTP, and AODV were implemented in the TinyOS [5]. We adopted RPL Contiki [17] implementation. We also performed experiments with Tymo, a TinyOS version of protocol Dymo. However, Tymo implementation did not show to be stable as reported in [18].

Table II. Simulation parameters

Parameter	Value
Base station	1 center
Number of sensors	100
Radio range (m)	100
Density ($nodes/m^2$)	10
Number of experiments	100
Bytes transmitted	1024
Path Loss Exponent	4.7
Power decay (dB)	55.4
Shadowing Std Dev (dB)	3.2

We run the experiments on the simulator for L2Ns TOSSIM [19]. We consider the base station to be a PC without memory restrictions and which can hold information about the entire network topology. we used the LinkLayerModel

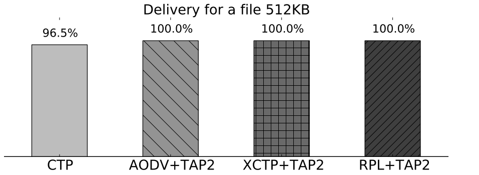


Figure 4. Transferring a 512KB file to a node 5 hops away from the root.

tool from TinyOS to generate the topology and connectivity model. We consider 10 different topologies. In each scenario were runs 10 simulations, totaling 100 runs. In the graphs presented, the curve represents the average and the error bars is the confidence interval of 95%. Table II presents the default simulation parameters.

B. Simulation Results

Figure 4 shows the percentage of delivery of a file of size $512KB$ sent from the root to a sensor node 5 hops away. XCTP+TAP2, AODV+TAP2, and RPL+TAP2 reach 100% of data delivery, because they allow feedbacks to be sent from data received between the two involved in the communication. We observed that CTP can transfer only 96.5% of the $512KB$, because it is not possible to request lost data or confirm received messages, since there are routes only towards the root. The impossibility of requesting the remaining fragments results in malfunctioning the application that is intolerant to data loss. We conclude that XCTP, AODV, and RPL favor the development of data transport protocols, providing routes that allow feedback messages to be exchanged among sensor nodes and the base station.

1) Robustness: To evaluate XCTP in terms of robustness, we elaborated experiments with different amounts of active flows (nodes transmitting data to root) and inserted network failures.

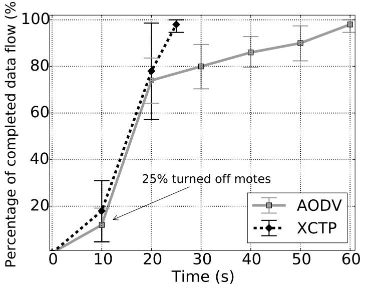


Figure 5. XCTP and AODV reactions in the occurrence of network failures.

Initially we compared XCTP and AODV with respect to the reaction in the presence of network failures. In this scenario, 5 sensor nodes transfer, each one, $1KB$ of data to root reliably and after $10s$ from the beginning of transmission we disable 25% of the network, without creating disconnected components in the network. Figure 5 shows in y-axis the percentage of flows that have completed the transfer of $1KB$ of data, the x-axis shows the elapsed time. In the first seconds of the simulation the two approaches are similar, being XCTP a little faster due to proactive construction of routes. After the shutdown of part of the network at $10s$, XCTP reacts quickly finding new routes to the root, the 5 sensor nodes operating with XCTP complete the transfer in approximately $25s$. AODV reacts slowly to topological change. AODV on average takes $60s$ to complete all data transfers, in some scenarios, AODV took over $200s$ to finish.

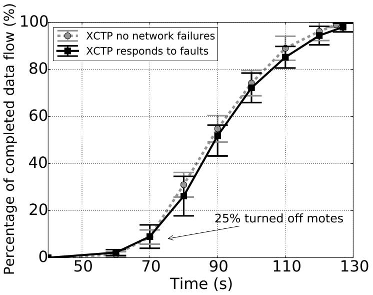


Figure 6. XCTP reaction in the presence of failures. 50 flows are active.

The experiment #2 has 50 active flows with the root. After $10s$, we shut down 25% of the nodes. Figure 6 shows XCTP behavior with and without failures in the network, in the picture are displayed the percentage of sensor nodes that concluded the data transfer per time. XCTP, even after the partial shutdown, quickly rebuild routes to the root and continues to transfer data. With average 2 minutes of simulation, all nodes end the data transfer. XCTP presents low difference of the behavior with and without network failures. This shows that XCTP is agile even in presence of faults and with many concurrent flows in the network. AODV is not shown in Figure 6 because it can not operate with more than 5 flows.

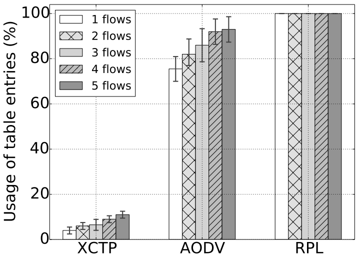


Figure 7. Memory consumption of the routing table per number of flows for the XCTP, RPL and AODV.

2) Scalability: To show that XCTP is scalable, we compared the size of XCTP, AODV, and RPL routing table. We did not compare with CTP because CTP table has constant size and stores only the next hop towards the root. Figure 7 shows the comparison between XCTP, AODV, and RPL in the use of routing tables varying the number of flows. We notice that with 5 flows AODV consume 100% of the routing table. When many flows coexist and the routing table is full, AODV is obliged to dismiss requests for new routes. Thus, AODV needs to wait for timeouts from old routes to expire so that new routes can be installed, which results in high reaction time for network fault and it prevents higher number of concurrent flows. Unlike AODV, XCTP consumes approximately 82% less from the table than AODV for the same amount of flows. RPL always installs all possible reverse routes, independent of

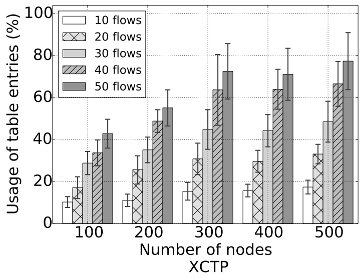


Figure 8. XCTP Reverse table use by varying the number of flows and sensor nodes in the network.

traffic demand. Some intermediate nodes will not be able to store all downward routes, thus, causing disconnection between some routes. Unlike RPL, XCTP attempts solve this problem with TTL-based policy over under-utilized routes and only stores reverse routes on demand.

Figure 8 shows that XCTP is robust and scalable. XCTP operates under the Reverse Table limit for different number of concurrent flows, with different topologies and amounts of sensor nodes in the network.

3) Control Traffic Overhead: Figure 9 presents the control traffic from five-hours experiments. XCTP and RPL control traffic are high at network start up, but they decrease and stabilize over time. XCTP sends fewer control packet than RPL because XCTP does not send additional beacons to build reverse routes.

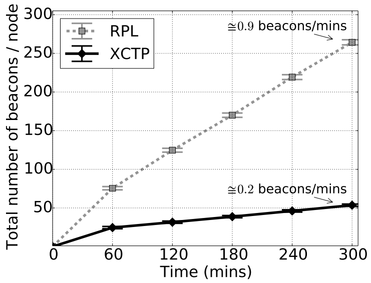


Figure 9. XCTP requires fewer control packets than RPL.

4) Memory Consumption: Table III presents the RAM and ROM footprint sizes of the components in our protocol stack with and without TAP2. XCTP adds little more than $1KB$ of code to CTP, requiring smaller amounts of RAM than when compared with AODV. Regarding the protocols in conjunction with TAP2, XCTP consumes less RAM than AODV.

Table III. CODE AND MEMORY FOOTPRINT IN BYTES.

	CTP	RPL	XCTP	XCTP+TAP2	AODV	AODV+TAP2
RAM	1505	6516	1812	1968	2119	2545
ROM	16204	46454	17942	18435	13868	14562

VI. CONCLUSION

We present XCTP, a reliable, robust, scalable, and efficient protocol for WSN. XCTP solves the problem of reliable data collection, extending the de-facto standard collection routing protocol CTP. XCTP allows bi-directional exchange of messages between a node and base station, extending the range of previously impossible applications with the CTP. For example, we show that XCTP favors the construction of transport protocols (TAP2), unlike CTP. In our experiments, XCTP reduces the number of states stored comparatively with AODV and RPL. XCTP is robust in the presence of network failures than AODV. Besides XCTP sends fewer control packet than RPL. This indicates that XCTP is an alternative for applications in L2Ns that are intolerant to data loss.

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