

Concurrent Transmission-based Packet Concatenation in Wireless Sensor Networks

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Abstract—Concurrent transmission, a novel communication paradigm, has been shown to effectively achieve reliable and energy-efficient flooding in low-power wireless networks. With multiple nodes exploiting a receive-and-forward scheme, this technique works effectively in one-to-many scenarios. However, application-level scheduling has to be introduced for data collection applications. In this paper, we propose Packet-in-Packet (PiP), an energy-efficient paradigm requiring no application-level scheduling for timely data collection in low-power wireless sensor networks. PiP builds on concurrent transmissions, exploiting constructive interference and the capture effect to achieve high reliability, low latency, and high energy efficiency. Moreover, PiP uses a packet concatenation capability to gather single-hop information in a best-effort manner. Experimental results show that PiP achieves high reliability in all experimental scenarios of a real-world testbed.

Index Terms—packet in packet, concurrent transmission, energy efficiency, flooding, wireless sensor networks

1. Introduction

As the first concurrent transmission (CT)-based flooding primitive, Glossy [1] has caught much attention in the community, recently. By exploiting a receive-and-forward scheme, sensor nodes transmit an identical packet at the same moment (within $0.5 \mu\text{s}$) to achieve a constructive interference and the capture effect. Glossy achieves energy-efficient flooding without causing broadcast storm problems and, thus, does not require any routing information in the network. In this respect, it differs from carrier sense multiple access with collision avoidance (CSMA/CA)-based IEEE standards, e.g., used by RPL [2]. Data collection (i.e., a many-to-one scenario) is one of the most important wireless sensor network (WSN) applications. The state-of-the-art collection protocols, such as CTP [3] and RPL [2], stick to CSMA/CA to deal with collisions. Inevitably, the back-off scheme of the CSMA/CA approach introduces longer latency and the re-transmission introduces higher overhead. In contrast, CT-based data collection has the potential of effectively providing high end-to-end reliability and low latency. This is, because CT-based protocols do not require media access control (MAC)-layer collision avoidance and network-layer routing. Nevertheless, current CT-based protocols used for data collection have to deal with two main issues: i) a flooding-based communication primitive

and ii) network-level scheduling. This type of communication primitive requires that the packet must be identical in one flooding round within the whole network, so that constructive interference can actually function. Besides, the capture effect is exploited to correctly receive a packet with the stronger signal strength when multiple senders are concurrently transmitting [4]. As a consequence, certain source nodes can never successfully transmit their packets to the receiver if they are not well enough globally scheduled. Even worse, when too many nodes concurrently transmit different packets, then destructive collisions occur more often. That leads to a decreasing packet delivery rate (PDR), a broken flooding process, and clock desynchronizations, to name a few.

To this end, we propose a new communication primitive – Packet-in-Packet (PiP) – for timely and reliable data collection in low-power WSNs. PiP uses CT, i.e., constructive interference and the capture effect, to inherit the advantages, namely: high reliability, low latency, and low energy consumption. Moreover, PiP exploits packet concatenation to achieve concurrent data collections from multiple neighboring nodes in a single transmission (TX) slot. By nature, PiP concatenates multiple packets from neighboring nodes in the air. Therefore, it requires neither a global scheduler nor a dedicated setup period.

In this work, we make the following contributions:

- We propose a communication scheme – *Packet-in-Packet* – for reliable and timely data collection in low-power WSNs.
- We introduce a novel hardware operation – a power amplifier (PA) operation – to realize concurrent packet concatenation in PiP.
- We implement PiP in Contiki [5] and carry out extensive experiments in local tests and in the Flock-Lab testbed [6], respectively, to evaluate the performance of PiP with respect to reliability.

The remainder of this paper is organized as follows. Section 2 details the design of PiP, followed by a performance evaluation in Section 3. Section 4 discusses related work, with a focus on Packet-in-Packet in low-power wireless networks. Section 5 provides concluding remarks.

2. Design of PiP

2.1. CT-based Collection

PiP is based on CTs, i.e., constructive interference and the capture effect, as derived from the essence of Glossy

[1]. In the course of data collection, there are typically various packets throughout the network. The contents of these packets are normally not identical in a collection round. Therefore, constructive interference does not function. The capture effect, in this case, however, enables the receiver to correctly receive a packet with the stronger received signal strength, if all the senders are highly synchronized (i.e., the time difference is less than $160 \mu s$). Generally, CT protocols exploit either global scheduling [7] or real-time in-network processing [4], so as to well handle CT-based data collection. PiP manages time synchronizations with network flooding (similar to Glossy), while employing a number of in-packet slots to collect the data from the single-hop neighbors in a single transmission round. However, when dealing with the capture effect, PiP does not manipulate power control as other approaches do. Instead, PiP relies on a type of hardware-based operation – a so-called PA operation.

2.2. PA Operation

PA is a type of electronic amplifier that enhances the power of the RF signal. In our research, we exploit that it is possible to control PA when one packet is being transmitted. We switch PA on and off via the registers MANAND and MANOR in CC2420 [8] during the transmission. Hence, a packet in PiP can be virtually considered as a number of PA-on and PA-off in-packet packets. The sender in PiP switches its PA on if it intends to transmit a new message, and switches PA off while there is nothing to transmit. Besides, the receiver receives the concatenated packet in the air without any PA operations by nature. Figure 1 shows the basic idea of the packet concatenation in PiP. In time slot 0, node H broadcasts a “beacon” packet to all the neighboring nodes. After the neighboring nodes have received the packet, they immediately transmit their own packets concurrently. For instance, in slot 1, every transmitter has its own corresponding time period (i.e., in-packet slot) to transmit its own packet (i.e., in-packet packet). A single transmitter switches its PA off when it has finished its transmission, e.g., node A switches PA off after it has transmitted its in-packet packet in the corresponding in-packet slot. As a result, with the PA operations, multiple senders in PiP are able to transmit their own in-packet packet in a single transmission slot.

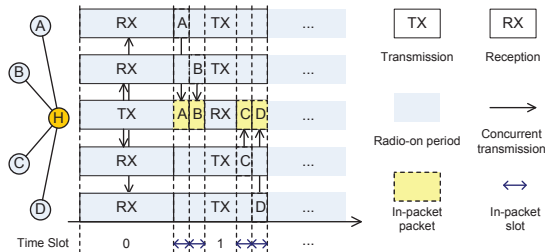


Figure 1. Single-hop packet concatenation of PiP. In node H, in-packet packets are received from node A, B, C, and D simultaneously.

2.3. Packet Concatenation

In PiP, we define one packet as a number of (e.g., seven) in-packet packets with fixed length. Correspondingly, the

sender switches PA on when there are in-packet packets to transmit and switches it off when there is nothing to transmit. The receiver detects the (identical) overlapped headers (i.e., the preambles and the start of frame delimiters (SFDs)) from multiple senders because of CTs. As long as there is one sender, which turns PA on during the in-packet slot, the receiver can receive the corresponding PA-on parts successfully. As shown in Figure 2, two senders concurrently transmit their own packets. The receiver starts to record symbols in the air once a header is detected, and stops based on the frame-length byte, i.e., the first byte after the header. In a normal case of CT, when the contents of two packets is identical, then the receiver can correctly receive the packet due to constructive interference. In this case, the first six bytes (i.e., the header and the length) are received based on constructive interference. Otherwise, when the contents is not the same, then the receiver can receive the packet with a higher power because of the capture effect. In the case of PiP, the capture effect still happens if multiple senders switch PA on at the same time, e.g., in in-packet slot 4.

In PiP, a sender is able to give away the “packet injection” opportunity to the others by switching PA off. In this case, it enables that the receiver can receive packets from all the neighboring senders rather than only a specific sender. For instance, the receiver in Figure 2 receives the in-packet packet from sender 1 since sender 2 turns PA off in in-packet slot 1. When it comes to a special case (e.g., in in-packet slot 5), where two senders both turn PA off, the receiver cannot detect anything in the air. However, in this case, the receiver still makes a soft decision [8], even though there is nothing in the air. As a result, a random sequence is placed as the contents of the PA-off part at the receiver, as illustrated in in-packet 5. Moreover, when the PA-off part passes and a following PA-on part arrives, then the PA-on part can be received and demodulated correctly because of the individual checksum in each in-packet slot. In this case, the received cyclic redundancy check (CRC) in the footer is meaningless for the receiver since a random sequence might exist in the packet. As a result, a received packet in PiP is validated by a software-based CRC at the receiver instead of a hardware-enabled CRC.

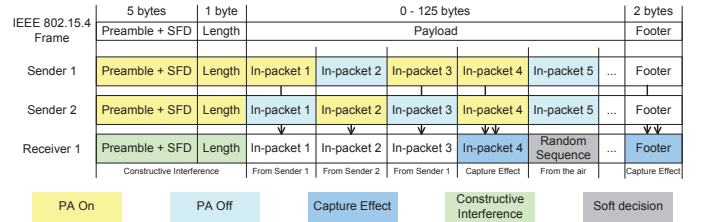


Figure 2. Packet concatenation. Two senders switch PA on and off to ensure that the receiver is able to receive various in-packet packets from all senders during one transmission round.

3. Performance Evaluation

In this work, we use the FlockLab testbed [6] for our experimental evaluation. FlockLab is located at ETH Zürich, Switzerland, and consists of 30 TelosB nodes inside and

outside of an office building. The topology of the testbed is shown on the website¹ of FlockLab. We use eight indoor observers out of 30 existing ones for our single-hop experiments. We focus on a key metric, i.e., reliability (indicated by PDR), to evaluate the performance of PiP.

3.1. Resisting the Capture Effect

In general, the capture effect has a strong influence on CT-based networks. Namely, when senders transmit the packets with different payloads to a receiver, the receiver would always receive the packet with the strongest signal. To some extent, the PA operation in PiP eliminates the capture effect in order to ensure that the receiver successfully receives other packets instead of the strongest one only.

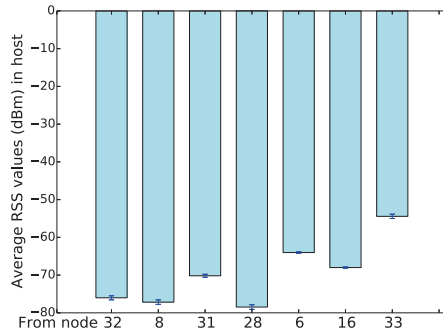


Figure 3. Single-hop RSS values in FlockLab.

As shown in Figure 3, we measure the received signal strength (RSS) of a set of neighboring nodes with node 3 (called “host”) as a receiver in FlockLab. The RSS values are measured by using 0 dBm TX power in all senders. Besides, we carry out a number of local tests and experiments in FlockLab, respectively, in order to figure out the influencing factors on the performance of PiP, such as RSS, relative distance between sender and receiver, and TX power. Figure 4 shows the results from the local tests with TelosB nodes. In the tests of non-equal distance, the further node is placed three meters away from the host (i.e., receiver) without obstacles, while the closer node is quite close (less than half a meter) to the host. We thus ignore this short distance and consider that the closer node is at the same point as the host. The distance difference between the further node and the closer node to the host is roughly three meters. In the tests of equal distance, both nodes are placed quite close to the host with the same distance of five centimeters.

In the tests of non-equal distance, the host receives the PA-on part from the further node when another sender turns PA off. As shown in Figure 4a, the PDR of the closer node is 100% due to the capture effect. The packets from both nodes could be received by the host if they are transmitted with PA operations. The PDR of the further node is only 50% if it transmits with PA operations (i.e., switching PA on and off accordingly), which is still much better than its PDR without PA operations. This is because, for the receiver, the concatenated packet is quite sensitive to the CT error (also mentioned in [9]). However, the distance difference is

doubled in terms of the CT error due to the back-to-back receive-and-forward scheme. The CT error for the two nodes is computed based on the distance difference and the speed of the radio signal: approximately $0.02 \mu\text{s}$.

To further prove whether CT with PA operations can function against the capture effect with respect to TX power, we use different levels of TX power in two source nodes, i.e., 0 dBm and -25 dBm , in the equal-distance scenario. This is because we attempt to exclude the influence of the relative distance difference to the host. As shown in Figure 4b, with PA operations, high PDRs are achieved by PiP, which are independent of the TX power levels. Otherwise, PDRs would be worsened by the occurring capture effect, e.g., the case of equal TX power without PA operations.

Similar experiments are also carried out in FlockLab. Figure 4c shows a worst case, where node 33 is much closer to the host than node 32. Even though, node 32 with PA operations can still obtain an average PDR of about 21%. Moreover, while in the case of equal distance to the host, nodes (node 8 and node 32) with PA operations are able to maintain an average PDR of more than 80%, illustrated in Figure 4d. To conclude, experimental results reveal that PiP works effectively to concurrently concatenate various packets from neighboring source nodes in a single-hop manner.

3.2. PiP with Pre-Reservation

Static pre-reservation means that the pre-defined corresponding in-packet slots are pre-reserved for the neighboring nodes to inject their own packets. In other words, each sender knows, which in-packet slot within the packet is preserved for its own transmission. Figure 5 illustrates the results for the single-hop cases with pre-reserved slot order in local tests and in FlockLab, respectively. PiP is a sink-initiated collection protocol. Therefore, it requires at least two transmissions for one reception (RX) – one for data pushing from the sink to the sources and one for data pulling from the sources to the sink. Thus, the number of RXs equals the number of transmissions (TX_N) plus 1. As Figure 5 illustrates, TX_N has a positive effect on the PDRs in most cases. That is, higher PDRs can be achieved by increasing the number of transmissions. We further extend PiP by a bitmap-based ACK scheme, so as to acknowledge those senders from which the packets have been received by the receiver. PiP is able to further improve the PDRs in both, local tests and experiments in FlockLab. In general, our results of the local tests in Figure 5a are better than the ones in FlockLab in Figure 5b. This is because we attempt to deploy the sender closer to the host in our local tests, which could alleviate the synchronization errors caused by the round time of transmission spent in the air.

4. Related Work

Santhapuri et al. investigated link-layer opportunities and challenges towards harnessing the feature of a so-called message-in-message (MIM) concept in [10]. They proposed an MIM-aware framework that reorders transmissions to enable concurrent communications. By continuously scanning for sync-words, their technique allows a transceiver to

1. www.flocklab.ethz.ch

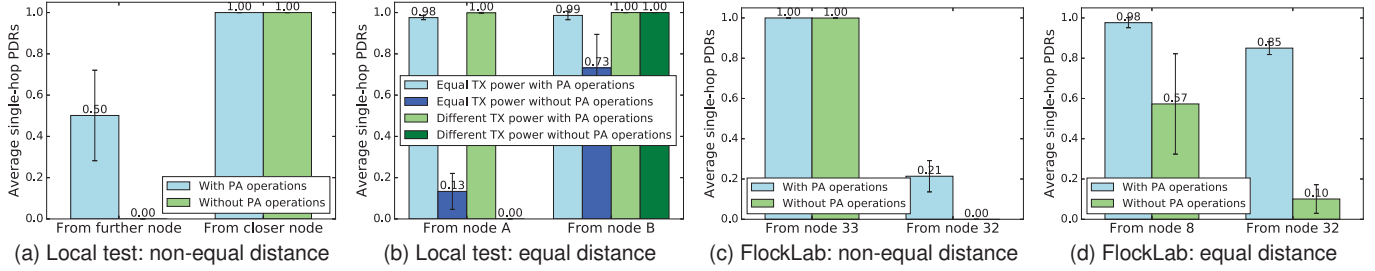


Figure 4. Single-hop packet concatenation with non-equal/equal distance cases in local tests and in FlockLab, respectively.

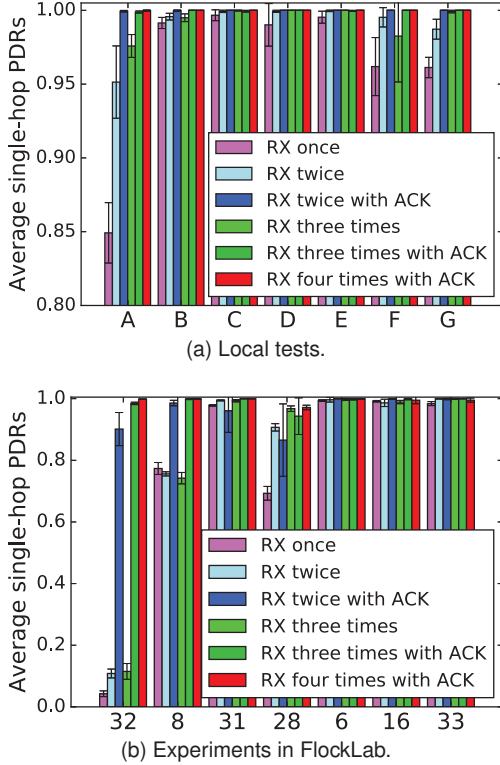


Figure 5. Packet concatenations with static pre-reservation in local tests and experiments in FlockLab.

disengage from the reception of an ongoing transmission and to lock onto a newly-started stronger one. More recently, König et al. in [9] proposed a class of wireless transmission schemes, that decouples synchronization headers from payloads in order to create new transmission primitives of a second sender. By only transmitting a synchronization header, a node is able to let the neighboring nodes receive fragments of a packet. Besides, portions of the payload of longer ongoing packets can be overwritten by exploiting the capture effect. The authors then explored two scenarios potentially benefiting from such schemes: crossing a network chasm and insertion of high-priority packets. Further, they examined the technique in these two scenarios. Results in a testbed showed that the packet received ratio can be increased from 5% to up to 30% in the case of network chasm. In the second scenario, the successful decoding of the injected packet in up to 70% of cases could be achieved.

5. Conclusion

In this paper, we proposed an energy-efficient communication paradigm based on IEEE 804.15.4 for timely data collection in low-power WSNs. PiP exploits both, constructive interference and the capture effect to achieve high reliability. Moreover, PiP maintains a packet concatenation capability to gather single-hop information in a best-effort manner. Experimental results revealed that PiP achieves high reliability in all experiments.

Acknowledgments

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