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Backing Out of Backscatter for Intermittent Wireless Networks

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ABSTRACT

Backscatter has emerged as the dominant paradigm for battery-free networking among the (potentially) trillions of devices in the future Internet of Things, partly because of the order of magnitude smaller energy consumption, but at the cost of collisions, low data rates, and short distances. This position paper explores the alternative approach: using low power, yet active radios to communicate among the battery-less swarm. We describe the challenges of using active radios in this context, including lack of tight time guarantees, high listening costs, and intermittent operation. While backscatter is promising, this paper hopes to broaden the conversation around alternative methods for networking the future IoT.

CCS CONCEPTS

• **Networks** → **Time synchronization protocols**; • **Computer systems organization** → **Sensor networks**; *Embedded software*;

KEYWORDS

energy harvesting, transiently powered computers, wireless sensor networks

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1 INTRODUCTION

Some years ago, the idea of battery-free backscatter communication was introduced: two RF-powered tags can communicate without the need of an active radio, by just modulating the reflected EM wave emitted by a carrier generator [5, 7]. More or less advanced modems were designed and tested to prove the feasibility of this technique, but the state of the art has not gone far beyond that yet. Furthermore, in backscatter communication, collisions are more difficult to resolve, and either data rates or communication range (or both) are very low. Backscatter methods also suffer from a reliance on in-place infrastructure like cell towers, Wi-Fi access points, or dedicated signal generators. Finally, and most importantly, backscatter communication alone does not overcome synchronization issues. For a packet to be transmitted, receiver and transmitter have to be active at the same time. Continuously-powered WSN (CP-WSN) nodes achieve this by synchronizing their radio schedules. For transiently-powered WSN (TP-WSN) nodes, two main synchronization challenges arise:

(C1) on-chip digital timers cannot capture the off time;
(C2) full control of active and inactive periods is not possible, since some restrictions are inherently posed by the harvesting circuit and the environment (i.e., active time is limited and sleep time is at least as much as the charging time).

Receiver and transmitter are affected by the same stochastic power-on/power-off behavior—experiencing repeated power failures (even tens per second)—thus making canonical time synchronization difficult to implement. Moreover, (C2) becomes even worse when using active radios, since higher power consumption results in shorter active periods.

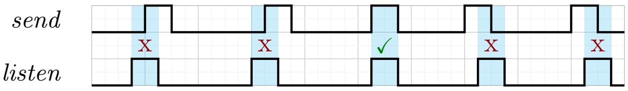

Figure 1: Packet loss under intermittency with a transmitter sending and a receiver listening. A packet is successfully delivered (indicated by a checkmark) only when the receiver is listening for the whole duration of the transmission.

Figure 1 shows an example of unregulated communication between two nodes. In this case, when sending a more or less long message, a high packet loss could result in very long delivery times. As the ratio between active and inactive time decreases, the chance of successfully sending packets from one node to another drops significantly. This effect can be mitigated by designing a more efficient energy harvester, sizing the super-capacitor accordingly and selecting low power microcontrollers and radios, but this is not a scalable solution. Instead, we envision a flexible and portable hardware/software solution to ameliorate synchronization between two (or more) TP-WSN nodes. To overcome challenges (C1) and (C2) respectively, the following should be developed:

(D1) a power-failure-resilient timekeeping solution;
(D2) a lightweight synchronization technique for TP-WSN nodes leveraging (D1).

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In this work, we suggest one implementation of (D1) using a *remanence timekeeper*, inspired by [3], and we provide a list of challenges that must be overcome to realize (D1) and (D2). Note that, even though we are targeting active radios, (D1) and (D2) should be applicable to backscatter communication as well.

2 BACKGROUND AND MOTIVATION

Low power communication protocols for Wireless Sensor Networks (WSNs) have been heavily researched for many years. For the last two decades several MAC-layer protocols have been proposed, all aimed at reducing energy consumption of battery-powered sensor nodes. Time synchronization plays an important role in this, since wasting radio activity results in large, unnecessary energy consumption. Within TP-WSNs, where timing constraints are very tight, wasted radio activity leads to high packet loss and low energy utilization: potentially starving other necessary on-device tasks.

2.1 Time Synchronization for WSNs

A common goal of time-synchronized MACs is to reduce *idle listening* of the receiving node by aligning transmission and reception with as little waste as possible. Two main classes of transmission can be distinguished for CP-WSNs: *synchronous* and *asynchronous*. The idea of the former is to synchronize all nodes' clock, to compensate their individual drifts, and then let nodes share a transmission schedule to abide by. Related work includes Reference-Broadcast Synchronization [2], pair-wise synchronization [8] and flooding time synchronization [6]. The goal of such methods is to have all the network nodes share a common clock with a fine-grained accuracy, also for timestamping purposes. Clearly, this clock granularity is not achievable for TP-WSNs nor relevant for our focus, that is reducing packet loss under intermittent operation.

With asynchronous transmission, nodes do not explicitly synchronize their clocks, but they formulate a radio schedule using their local relative time. The authors of WiseMAC [1] provided one of the earliest solutions to asynchronous WSN communication. Sun et al. [9] proposed an innovative asynchronous technique in which the receiver initiates the communication by sending a beacon when it is ready to listen, and waiting for a response by a possible transmitter. WiseMAC was revised and improved by Le et al. [4] to work with energy harvesting devices by importing clock drift corrections into asynchronous communication. Despite the relevance of this work, the authors targeted energy harvesting devices operating under energy neutral operation (ENO). When the device is consuming less energy that it is currently harvesting, it is said to be in the ENO condition.

The research in this work aims at maximizing energy usage, by varying active and sleep times, yet meeting the ENO condition. Nodes of such networks can still use their on-board timers, which have different drifts than remanence timekeepers, and effectively are not treated as intermittently powered. When energy conditions and power consumption do not allow ENO operation (i.e., under intermittent operation), alternative methods must be used.

2.2 Packet Loss for Transiently-Powered WSNs

When it comes to TP-WSNs, where it might be the case that nodes can exchange only one small packet before experiencing a power failure, synchronization is not just beneficial, but essential. Consider the case of Figure 1. The transmitter sends a packet as soon as it reboots, then its energy buffer depletes before it can send another packet, so the node turns off and starts charging until the next reboot. Similarly, the receiver listens for incoming packets for the whole duration of its active period, from reboot to power failure. In such a scenario, the packet loss could be significant.

Table 1: Packet loss (PL) under intermittent power harvested at distances d from an RF exciter. The percentage, and the average (radio) active time, of transmitter and receiver are reported. PPS is the number of packets sent per second.

		TX radio on		RX radio on		
d [cm]	PL [%]	[%]	avg [ms]	[%]	avg [ms]	PPS
33	91.94	9.97	23.13	23.36	17.02	43.24
40	95.75	7.55	30.54	16.29	22.29	32.74
50	98.38	4.03	57.29	10.37	32.66	17.46
66	99.52	2.41	95.83	7.21	44.96	10.44

To provide an example, we configured two devices in a way that the packet loss approximates zero when energized by a continuous power source. The two nodes were composed by a TI MSP430FR5994 low power microcontroller, a TI CC1101 low power active radio and a Powercast P2110 RF power harvester connected to a 1-mF energy buffer. The energy was generated by a Powercast TX91501 RF exciter emitting at 915 MHz with a power of 1 W EIRP from a 60° directional antenna. The nodes were placed at four distances from the exciter, 33, 40, 50 and 66 cm, without any obstacle between transmitting and receiving antennas. The transmitter was sending four-byte packets at 76 kBaud/s with a power of −30 dBm. By varying the distance from the exciter, we tested different values of the ratio between active and inactive time of the two nodes, which we refer to as duty cycle. Table 1 summarizes the measured packet loss. Even under favorable harvesting conditions, at only 33 cm from the generator, a 92 % packet loss is experienced, and by only doubling the distance the packet loss is almost 100 %. Note that no parameters were changed during experiment other than the exciter-to-node distance. Therefore, the resulting performance metrics (packet loss, radio on time and PPS) are a result of this variable only.

Adjusting the hardware configuration might lead to different results, e.g., increasing the size of the super-capacitor would enlarge communication windows, or increasing the data rate would require shorter rendezvous intervals. Nevertheless, a general solution target worst-case scenarios, in which the communication window can be as small as possible, as long as large enough to guarantee packet delivery when transmitter and receiver are synchronized.

3 TRANSIENTLY POWERED TIMEKEEPER

A remanence timekeeper exploits physical properties of an RC circuit to continuously keep track of time when there is no energy available to power a digital timer [3]. It achieves this by storing some charge on a small capacitor when the microcontroller has power, and letting the capacitor discharge through a large resistor upon a power failure. Then, at reboot, the voltage level across the capacitor will give an indication of the time elapsed since it had

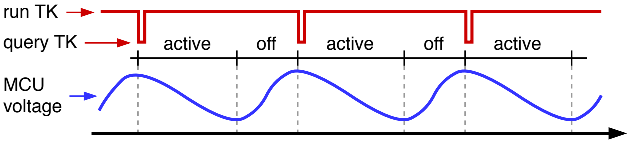

Figure 2: Timekeeping strategy. Run timekeeper (TK) to capture the whole power cycle (active plus off), query on reboot.

been recharged. Ideally, it would be enough to have a resistor R, a capacitor C, an ADC to sample the capacitor's voltage V and the relevant equation of a RC circuit to be able to use the timekeeper:

$$t = -RC\ \ln(V/V_0)\,. \tag{1}$$

The way timekeeping is done in Mayfly [3] presents two major problems. First, the remanence timekeeper is only used to time inactive intervals, i.e., when the MCU is off. This makes it more cumbersome to measure active times, as using a digital timer requires periodic checkpoints of the timer value into non-volatile memory, at the cost of some energy and time overhead, which increases when a higher resolution of timer checkpoints is needed. As the device will never know exactly when to checkpoint, this creates an additional error in time measurement. Since the whole power cycle has to be measured (active and inactive period) to achieve time synchronization, the timekeeper could be used to time the active period as well (like in Figure 2). Furthermore, (1) is used without accounting for real electronics' behavior. In actuality, capacitor and resistor never match their nominal values, the ideal current model does not hold because of leakages and other parasitic capacitance and resistance are spread through the circuit. A circuit-tailored calibration routine could yield better results and render tighter synchronization and timing guarantees.

It is of relevant importance to solve these two issues, because energy-harvesting networks require accurate and low power time synchronization. Only a refined timekeeping technique would enable low-packet-loss wireless communication.

4 FUTURE WORK

As a first step, the challenges presented in Section 1 must be solved. To recap, TP-WSN nodes need (i) accurate, intermittency-safe timekeeping, and (ii) lightweight time synchronization based on (i).

4.1 Timekeeping

Achieving timekeeping accuracy in the order of milliseconds, some improvements upon [3] are required. The designed component, and its software, should be also characterized for accuracy and precision. To summarize, we suggest the following action items:

(T1) the timekeeper must be used to capture entire power cycles, i.e., active and inactive intervals, as explained in Section 3;
(T2) a software calibration, as motivated in Section 3, must be developed and run before deployment of each network node.

4.2 Time Synchronization

After developing and characterizing the timekeeper architecture, an intermittency-safe time synchronization protocol can be designed and deployed onto TP-WSN nodes. More or less complex methods to achieve synchronization can be devised. Such protocols become feasible using the new timekeeping architecture.

When the energy availability is stable due to a fairly constant harvesting condition, the wake-up rate of transmitter, i.e., the packet rate, is also somewhat stable. In this case the receiver could activate at the same rate. If it cannot catch up with the transmitter's wake-up rate due to scarcer energy availability, it can try to listen at a rate that is a sub-multiple of the transmitter's rate. On the other hand, when transmitter and receiver have a wake-up rate that is not stable, more complex protocols should be applied to minimize the packet loss. This could involve restrictions on the wake-up rate and two- or three-way handshakes.

Research explorations we consider necessary for a synchronized intermittent wireless network include:

(S1) modeling of synchronization requirements based on the timekeeper's precision and accuracy;
(S2) design of time synchronization protocols for more or less predictable energy harvesting patterns;
(S3) deployment and evaluation of the designed protocol onto real energy-harvesting wireless network nodes.

We want to emphasize again that the time synchronization we envision would be applicable to any physical layer of choice, including the ultra-low power backscatter.

5 CONCLUSIONS

We have analyzed the main challenges arising from transiently powering wireless sensor networks: specifically time synchronization. To lay the foundations for future research we have identified directions to realize an accurate, low power, intermittency-safe timekeeping to be used for transiently powered wireless networks.

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