BLISP: Enhancing Backscatter Radio with Active Radio for Computational RFIDs

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***Abstract*—We demonstrate the world's first hybrid radio platform which combines the strengths of active radio (long range and robustness to interference) and Computational RFIDs (low power consumption). We evaluate the Wireless Identification and Sensing Platform (WISP), an EPC C1G2 standard-based, Computational RFID backscatter radio, against Bluetooth Low Energy (BLE) and show (theoretically and experimentally) that WISP in high channel attenuation conditions is less energy efficient per received byte than BLE. Exploiting this observation we design a simple switching mechanisms that backs off to BLE when radio conditions for WISP are unfavorable. By a set of laboratory experiments, we show that our proposed hybrid active/backscatter radio obtains higher goodput than WISP and lower energy consumption than BLE as stand-alone platforms, especially when WISP is in range of an RFID interrogator for the majority of the time. Simultaneously, our proposed platform is as energy efficient as BLE when user is mostly out of RFID interrogator range.**

I. Introduction

Most low power wireless sensor nodes use active radio transmission techniques, such as Bluetooth Low Energy [2], to transport data. While active radios are becoming better with each year (in terms of throughput and range), the power consumption expenditure of radio communication can still be much larger than the power expended for computation [3]. This indicates that there is still a lot to be done to make wireless sensor nodes more power efficient, despite many years of research in low power electronics. One approach to reducing energy consumption of the wireless front end is by not actively transmitting, but instead modulating the reflection of power emitted by an external transmitter—as with RFID-based Computational RFIDs (CRFIDs) [4].

A. Problem Statement and Research Question

Unfortunately the transmission technique used by CRFIDs, i.e. backscatter, has non-ideal characteristics compared to active radio. While power efficient, backscatter is susceptible to distortion by the environment [5, Fig. 4]. Additionally, the path loss for backscatter signals is very different than for active transmissions. Active transmissions have a signal-to-noise ratio which approximately decays with the square of distance. For backscatter radio, this decay approximates the fourth power of distance [5, Sec. 2.2]. Hence, the energy wasted due to lost data increases. At the same time, active radios, although more resistant to interference, consume more energy than backscatter radios. The difference in power consumption is mostly due to the need to actively emit RF power instead of reflecting preexisting signals. This robustness/energy efficiency trade-off of active and backscatter radio calls for connecting these platforms. Practically, many real-life situations call for an extension of backscatter by active radio.

Example: It is shown in [6] that cows have preferred regions (hotspots) within the paddock in which they spend the majority of their time. In [6, Fig. 3] the number of hotspots (covering less than $20\,\mathrm{m}^2$) is limited to six, and is spread over a large area ($\approx 230\,\mathrm{m}^2$). To monitor cattle movement (C)RFID would cover the hotspot area, while active radio would cover transitional movement.

The research question is then: *What energy consumption and transmission reliability improvements can one get by exploiting the combined benefits of active and backscatter radio?*

B. Contributions of This Paper

To answer this question we design a new heterogeneous radio sensor node combining both active and passive radio in one device. We call this platform BLISP—a composition of **B**luetooth **L**ow Energy (state-of-the-art Commercial off-the-Shelf (COTS) active radio platform for consumer applications [2]) and W**ISP** [7] (state-of-the-art CRFID). This proposed platform consists both of low-cost experimental hardware combining the two radios in one system, and a radio selection technique (implemented in software) to choose the appropriate radio for the appropriate situation while trying to optimize both reliability and energy efficiency. To show the benefit of BLISP, the complete system is evaluated in replicable static and mobile scenarios using a COTS RFID reader and a modified smartphone-attached RFID reader.

The contributions presented in this paper are:

Supported by the Dutch Technology Foundation STW under contract 12491 and in part by a Google Faculty Research Award, a Google PhD fellowship, the Intel Science and Technology Center for Pervasive Computing, and NSF award CNS-1305072.

Another version of this work is available in [1].

Contribution 1: we provide a set of simple theories, supported by experiments, showing the benefit of connecting active and backscatter radio platforms;

Contribution 2: we show the benefit of using BLISP as an extension to CRFID applications by demonstrating that it is possible to transmit more data compared to an out-of-range CRFID while only increasing energy consumption per byte by ≈15 % compared to Bluetooth Low Energy (BLE).

Contribution 3: we show the benefit of using BLISP as an extension to BLE applications by demonstrating the possibility of transmitting the same amount of data compared to BLE while decreasing energy consumption per byte by more than 50 %.

The rest of this paper is organized as follows. Section II reviews related work. Research motivation is provided in Section III, followed by Section IV discussing a simple feedbackless radio switching method for BLISP. Section V presents experimental platform used to verify the quality of the proposed switching mechanism of which the results are discussed in Section VI. A discussion on limitations and future work is given in Section VII, and the paper concludes with Section VIII.

II. Related Work

We start by reviewing literature pertaining to active and backscatter radios and connection thereof into an hybrid device.

A. Computational RFID

The use of CRFID for wireless sensor applications has been advocated by many papers including [8], [9]. The only stable CRFID [4] implementation currently available is Wireless Identification and Sensing Platform (WISP). The communication protocol used by WISP is the industrial standard EPCglobal Class 1 Generation 2 (EPC C1G2) RFID protocol. Although completely battery-autonomous, CRFID has intrinsic limitations: Limited channel robustness, as evaluated by [5]; and limited RF power transfer efficiency results in an intermittent power supply. A solution to the continuous power supply problem proposed by [10] exercises a hybrid power solution based on RF power harvesting and an energy storage device. While this significantly improves CRFID energy supply stability, it does not solve the robustness problem.

B. Bluetooth Low Energy

Active (low power) radio systems are less susceptible to interference compared to backscatter communication. However, they bring the disadvantage of higher energy consumption. There are multitudes of low power active radio platforms, and reviewing all options is not in the scope of this work. However, there is one believed to be broadly adopted, with more than 30 billion devices expected to reach the consumer market by 2020 [11]: BLE—the newest version of the Bluetooth protocol optimized for low energy applications[1]. Works by [2], [15] experimentally evaluate the performance of BLE, while [16] shows the energy consumption of BLE compared to other popular active radio technologies. No studies comparing the energy consumption of BLE with a backscatter-based CRFID have yet been published to the best of our knowledge.

[1] For example, recent standards like SigFox [12], LoRa [13] or IEEE 802.15.4k [14] could be used, and are expected to have even lower energy consumption than BLE. We will not use them in this work as they are not (yet) easily accessible for experimental evaluation, nor broadly adopted.

C. Multi-Radio Systems

A combination of backscatter radio and active radio seems to be the logical step to solve the imperfections of both systems. Again, to the best of our knowledge, no such hybrid implementation exists. One obvious way of using BLE to extend the RFID range is to use multiple RFID readers which are coupled using BLE, as proposed for different radio types (with node-to-node communication) by [17]. This approach, unfortunately, cannot be used for BLISP because state of the art CRFIDs cannot communicate with other CRFIDs without the interrogator. The only hybrid active/backscatter platform we are aware of is [18], which uses BLE to reprogram a backscatter testbed, and does not use the active radio to improve reliability.

Authors of [19] propose a method of using BLE as a physical transport layer for an RFID protocol. A backscatter-BLE method is proposed in [20], which allows a backscatter device to synthesize BLE packets but which has similar channel constraints as conventional backscatter. In the non-backscatter context, an approach to combine multiple heterogeneous radios by [21] uses acknowledgement delay and machine learning mechanisms to optimize system performance. All above-mentioned multi-radio platforms rely on acknowledgements from the receiving party and/or active radio transmissions.

D. RF Power Harvesting

Considering literature related to energy storage in CRFID, we need to mention [10] again proposing to store energy in battery/capacitor for future use and [22] where energy storage from rectifying Wi-Fi signals has been proposed.

III. Motivation for Combining Active and Backscatter Radio

To understand why backscatter is not always the most efficient radio technique, we introduce a simple analytical basis to bring insight into the design of BLISP. The theoretical model is followed by experimental results verifying the theory.

A. Difference in WISP and BLE Radio Efficiency

We start with the analytical model.

1) Analysis: Assume a hybrid radio platform composed of $i = \{1, \ldots, n\}$ independent radio technologies (such as backscatter and active radio). We characterize the energy per successful transferred byte for radio i as $E_{\text{byte},i}(d) = E_{\text{tx},i}/B_{\text{rx},i}(d)$, where $E_{\text{tx},i}$ is the total amount of energy spent in transmitting data and $B_{\text{rx},i}(d)$ is the number of received bytes for distance $d \in [0, d_{\max})$. Generalizing [23, Sec. III-A]

$$B_{\text{rx},i}(d) \triangleq \frac{L}{L+H}\left[1 - \operatorname{erfc}\left(f_i(d)\right)\right]^{L+H}, \tag{1}$$

where L and H are the payload size in bits and the amount of overhead in bits, respectively, and $\operatorname{erfc}(.)$ is the complementary error function. We define the signal quality decay function $f_i(d) = (d/a_i)^{-r_i}$, a_i as radio-intrinsic correction value and r_i as loss coefficient. For example, a typical value of $r_i = 2$ for active radio or $r_i = 4$ for backscatter radio. Now, based on the above model we pose the following lemma.

Lemma 1: Any hybrid radio composed of n radios has limited range after which energy consumption per byte is infinite.

Proof: $\forall n \lim_{d\to+\infty} B_{\text{rx},i}(d) \rightarrow 0 \Rightarrow E_{\text{byte},i} = E_{\text{tx},i}/B_{\text{rx},i}(d) \rightarrow +\infty$ which completes the proof. □

Corollary 1: Defining $\mathrm{E}(d) \triangleq \{E_{\text{byte},1}(d), \cdots, E_{\text{byte},n}(d)\}$ if $\exists_{E_{\text{byte},i}(d)\in \mathrm{E}(d)} \forall_{E_{\text{byte},j}(d), i\neq j} E_{\text{byte},j}(d) < E_{\text{byte},i}(d), \forall d$, then radio j can be removed from designing a hybrid radio.

Corollary 2: The maximum range of a system is limited by the radio with the largest range.

Corollary 3: At distance d the lower bound of the hybrid radio energy consumption per byte is given by the radio with the lowest energy consumption at that distance.

2) Measurement: To verify this simple analytical model we need to measure the consumed power of each radio as a function of the signal loss. We first introduce the selected hardware for BLE, WISP and finally the measurement setup.

a) Bluetooth Low Energy—Transmitter/Receiver: We selected the Nordic Semiconductor PCA10005 evaluation module with an NRF51822 BLE System on Chip (SoC) [24] as BLE transmitter. The software used on the BLE radio is a customized firmware version (source code is available upon request or via [25]) transmitting only standard advertising messages [11] at a constant rate of 120 Byte/s=0.96 kbit/s, which is comparable to 0.65 kbit/s of [26, Sec. III-B]. BLE has a maximum packet size smaller than the selected payload (i.e. 24 Byte) therefore each transmission consists of multiple packets. A second identical NRF51822 module is used as BLE receiver—continuously logging advertisement messages send by the BLE transmitter.

b) Computational RFID—Transmitter/Receiver: We select WISP 5 as a state-of-the-art CRFID platform [7]. The WISP 5 used for experiments has the RF energy harvester disabled by desoldering the output pin of the buck converter. This modification simplifies the energy measurement, as the energy provided to WISP 5 is not fluctuating in time as in the case of harvested energy. The WISP 5 firmware is adapted (see again [25]) to transmit with the same data rate as BLE. Again, as in the case of BLE, since the maximum payload of WISP 5, i.e. 12 Byte, is smaller than 120 Byte each message consists of multiple packets. The RFID reader is an Impinj Speedway R420 [27], controlled via SLLURP Low-Level Reader Protocol (LLRP) library [28], and connected to a panel antenna [29].

Based on observations by [30, Sec. 4.1] we have chosen to use the EPC C1G2 Electronic Product Code (`EPC`) field as our data carrier instead of the `Read` command. Using the `EPC` field cuts down on the protocol overhead because it halves the amount of roundtrips [31, Sec. 6.3.2.12.3]. According to [31, Sec. 6.3.2.1.2.2] the length of the `EPC` field may be set between zero and thirty one words. While it is possible to have WISP transmit longer `EPC` values to reduce the overhead, this increases the probability of corrupted messages [23].

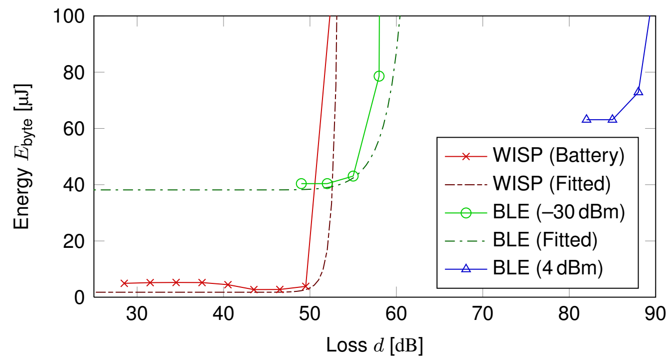


Fig. 1. **Energy per byte over distance for WISP and BLE.** The dashed data points are extrapolated, the constant power consumption for the BLE radio and all data being received, yields constant energy per byte. Fitted plots are based upon (1). Parameters for fitted WISP curve: $a_i = 30$, $d_i = 4$, $E_{\text{tx},i} = (L + H)5\,\mu\text{J}$ with $L = 96$ and $H = 320$. Parameters for fitted BLE curve: $a_i = 87$, $d_i = 2$, $E_{\text{tx},i} = (L + H)21\,\mu\text{J}$, L and H are equal to WISP.

c) Measurement Setup: We measure energy per byte at the receiver (separately for BLE and WISP) as a function of signal attenuation. This is realized with two signal attenuators [32] connected in series. These attenuators limit the signals bi-directionally, and therefore both uplink and downlink are attenuated at the same time. Both BLE transmit/receive evaluation boards used are equipped with an antenna connector allowing attenuators to be inserted directly into the transmission channel. WISP, on the other hand, does not provide such an antenna connector and therefore it is positioned at a fixed distance of 50 cm from the interrogator antenna which is then connected to the RFID interrogator via the attenuators.

The BLE module [24] has an uncalibrated transmission power setting via the API of the S110/S120 (transmitter/receiver, respectively) softdevice. The highest (4 dBm) and lowest (–30 dBm) transmission power are tested. The RFID reader is tested at its maximum transmission power (32.5 dBm).

We measure the power consumption of both radios using a self developed, buffered, differential, sensing circuit monitoring the voltage drop over a 100 Ω shunt resistor in series with the Device Under Test (DUT). This circuit is coupled to a Tektronix MDO4054B–3 oscilloscope [33] to measure power over time which is used to calculate the energy consumption. Schematics of this device are available upon request or at [25].

3) Measurement Results: The relationship between energy per byte and signal loss, as measured for both active and backscatter radio and complementary fitted plots, is shown in Fig. 1. As expected, the WISP—while more energy efficient in good channel conditions—also has a shorter range of operation. Instead of a gradual increase in energy consumption per received byte, at one point the energy per byte metric starts to rapidly increase for both platforms. This “brick wall” effect [23, Sec. V] is caused by an increase in bit errors, causing whole packet loss and therefore requiring more transmit attempts per successfully received byte.

B. Do Alternatives Exist to Hybrid Active/Backscatter Radio?

The question remains of whether, in the light of this observation, the hybrid radio platform is the only solution which improves energy efficiency and transmission range of CRFID. We review the alternatives and provide our answer.

1) Low Power Active Radio with Battery: The simplest alternative to the hybrid platform would be a connection of a sufficiently large battery and BLE radio.

Limitation: Unfortunately, all batteries will eventually deplete, leading to expensive battery (or even whole device) replacement. For battery replacement, the device must be physically accessible, as it is impossible to wirelessly restore the energy level of the empty battery without an energy harvester.

2) Power Harvester with Active Radio: Wireless RF power harvesters solve the physical accessibility and battery constraint.

Limitation: Inefficiencies in RF power harvesters, energy storage, energy conversion, and energy transmission through RF waves, mean that no power harvester and active radio combination will be as energy efficient as a backscatter radio.

3) Backscatter Radio with Improved Channel Coding: The operational reliability and robustness of communication of CRFIDs could be improved by adding a more extensive channel coding mechanism. For example: WISP is currently limited to the FM0 coding [31, Sec. 6.3.1.3.2.1], in which each bit is represented by one signal alternation for each symbol. Miller coding methods [31, Sec. 6.3.1.3.2.3] have redundant alternations within each symbol, reducing the possibility of lost messages.

Limitation: Channel coding would make CRFID more robust (i.e. shift the WISP curve to the right in Fig. 1), still keeping CRFID susceptible to reflections and destructive interference. Finally, we conjecture, this would still not make WISP as energy efficient as BLE in a broad attenuation range.

IV. Channel Estimation Methods for Hybrid Active/Backscatter Radio Platforms

We propose a method of estimating the backscatter channel and use this estimation to select between backscatter and active radio on-the-fly. We start with revising unsuitable solutions.

A. Backscatter Channel Quality Estimation Methods: Review of Unsuitable Solutions

Because backscatter radios behave differently than active ones, typical channel estimation methods do not directly apply.

1) EPC C1G2 Protocol Feedback: The de facto standard method of assessing packet reception rate is to query the receiving party if it indeed received a packet. Most protocols rely on receive acknowledgments for (all) packets.

Limitation: Within the EPC C1G2 [31] protocol there are no standard ways to guarantee the successful reception of `EPC` values transmitted by a tag. The default method of awaiting an Acknowledgement (`ACK`) message for each transmitted data message is therefore not possible. The exclusion of this functionality is logical for standard RFID tags, as they are computationally limited, transmit unchanging identifier, and most likely could not handle retransmissions. Transmitting data back to a CRFID also implies that CRFID should handle computationally hard, and a protocol-wise large overhead inducing EPC C1G2 `write` accesses.

2) BLE Protocol Feedback: The more responsive BLE channel could be used to provide a feedback for the reception of RFID packets transmitted by CRFID.

Limitation: The use of a separate radio channel could increase RFID reliability because the channels might break down under different circumstances. However, it might also decrease reliability because the BLE channel might be broken while the RFID channel is working. Practically, including a BLE radio in receiving mode will also dramatically decrease the energy efficiency of a hybrid platform, as the radio has to listen for an extended (worst case: continuous) time.

3) RSSI Strength Feedback: Neither CRFID hardware nor EPC C1G2 protocol has a built-in support for Received Signal Strength Indication (RSSI) measurement on the RFID transmission. A coarse method to estimate the vicinity of RFID reader is by measuring the amount of energy harvested by the CRFID. If a tag is close to a reader, it is easily possible to harvest energy, while if a tag is far away it would be almost impossible to harvest it. The BLE radio has native support for RSSI measurements on the received messages.

Limitation: Measuring RSSI for the signal originating from the interrogator and received by the backscatter radio does not directly correlate with the channel quality for backscatter data (as there is no constructive interference, as explained in Section I-A). While the interrogator knows the RSSI, the backscatter device cannot reliably determine it. A CRFID could query the RFID reader for its RSSI as measured by the reader but this would induce a lot of overhead on both sides. I BLE should be placed into listening mode in order to retrieve RSSI values, which is more power consuming than the transmission mode. Therefore, enabling BLE only for channel estimation without using it for data transfer is a loss of energy.

B. Proposed Channel Quality Estimation Method

For the BLISP system we propose a novel, less standard, way of estimating the channel.

Proposition 1: Tracking the number of EPC C1G2 `RN16` `ACK` messages in handshake can be used to estimate the backscatter channel quality.

Proof: (Sketch) If RFID interrogator and tag perform a multipart handshake, the backscatter channel is usable to transfer data. Work of [5] proposed an approach for setting an interrogator to its optimal settings based on both measured RSSI and packet loss. However, packet loss-based, estimations can also be performed on the tag instead of the interrogator. Part of this handshake is the tag sending the reader a random number (`RN16`), which the reader should acknowledge by an `ACK` message containing this random number. To reach the `ACK` both channels (to and from) the CRFID tag need to be in a state good enough to transmit a payload. By measuring the number of handshakes and testing this number to be at least the same as the amount of packets we expected to transmit, we are able to estimate quality of the backscatter channel. □

V. BLISP Design

We are now ready to introduce BLISP, our hybrid backscatter and active radio platform, to help exploit the main trade-

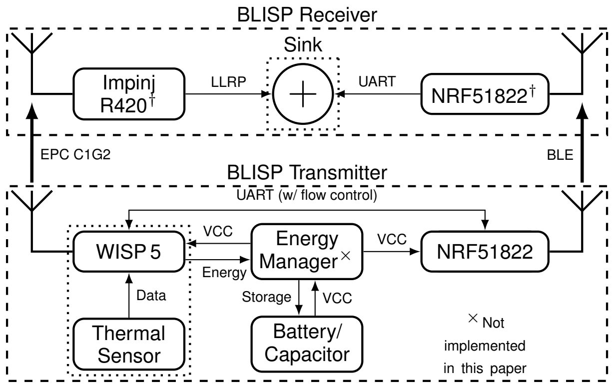
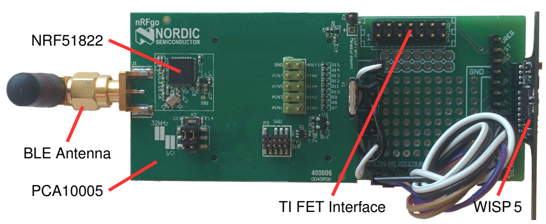
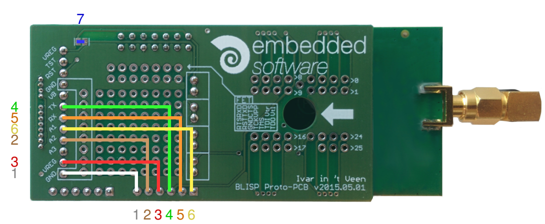


Fig. 2. **Overview of the BLISP system consisting of one transmitter and one receiver.** The temperature sensor providing data is part of WISP but displayed separately for clarity and completeness. All displayed connections depict a flow of energy or data and do not directly correspond to physical connections. For a detailed description of the physical connections see [25]. †For the mobile reader experiments the Impinj R420 is replaced by an MTI MINI ME, and the NRF51822 by the BLE receiver of a Samsung Galaxy S3.



(a) The top side of the BLISP with annotations for the most important components. Please note that the WISP antenna is not fully shown.



(b) Bottom side of the BLISP. Symbolicaly illustrated directional connections by color, as numbered: (1) **white**: ground; (2) **brown**: clear to send; (3) **red**: power supply; (4) **green**: WISP to BLE serial channel; (5) **orange**: BLE to WISP serial channel (unused); (6) **yellow**: ready to send, and (7) **blue**: power supply.

Fig. 3. **The BLISP PCB as seen from top (Fig. 3(b)) and bottom (Fig. 3(a)).** PCB design files are available upon request or from [25].

offs as proposed in Lemma 1 and Corollaries 1 to 3. The BLISP infrastructure mainly consists of two parts: (i) a COTS RFID interrogator combined with a BLE receiver; and (ii) our multi-radio sensor node—the BLISP. To provide a flexible platform we opt to combine two readily available radios instead of developing our own, single silicon, platform.

A complete system level overview of the BLISP is shown in Fig. 2. The main design principle behind BLISP is the absence of any algorithm on the host side: the host only merges the multiple data streams received by the different radios.

A. BLISP Hardware Architecture

The chosen radio modules for this platform are the same as described in Section III-A2. PCB has been designed to ease

TABLE I
SETUP PARAMETERS OF DATA AGGREGATORS

Component	Parameter	Mobile BLISP RX	Static BLISP RX
Host Device	Model	Samsung Galaxy S3	Lenovo T530
	Software	Android 4.3	Linux 3.13.0
RFID Reader	Model	MTI MINI ME	Impinj R420
	TX Power	18 dBm	32.5 dBm
	RX Sensitivity	–84 dBm	–82 dBm
	Antenna Gain	2 dBi	9 dBi
	Link Frequency	640 kHz	640 kHz
	Coding	FM0	FM0
	Session	2	2
	Q-value	5	n/a
	Duty Cycle	100%	100%
BLE Receiver	Model	Samsung Galaxy S3	Nordic NRF51822
	Duty Cycle	100%	100%

the connection of the two separate radio platforms, see Fig. 3. The PCB connects the active and passive radio, and provides means for radio collaboration and energy distribution.

1) Active Radio: We use the same NRF51822 BLE module as described in Section III-A2.

2) Backscatter Radio: As backscatter radio we also use the same WISP 5 as described in Section III-A2.

3) Radio Collaboration: A communication channel is needed to convey desired state information for the active radio and to share sensor values between the two separate radios. The NRF51822 BLE module has a silicon bug causing high power consumption by perpetually keeping non-vital microcontroller peripherals enabled [34, Id 39]. This bug unfortunately affects all conventional (digital) communication channels including General Purpose Input/Output (GPIO)-interrupts rendering them useless as low power wake-from-sleep devices. The low power analog comparator peripheral is not affected by this bug, therefore this peripheral is used as wake-up signal enabling the high throughput Universal Asynchronous Receiver/Transmitter (UART). The BLE radio also uses digital output as CTS signal.

4) BLISP Receiver/Sink: The receiving side of BLISP consists of two receiving radios matching the two transmitting radios on the BLISP. In contrast to [21], the BLISP receiver is as simple as possible and only merges the data streams from the receiving radios. Because the host does not make decisions about which radio to use, the BLISP can switch without synchronization mechanism. We present two host setups: (i) a fixed receiver; and (ii) a mobile smartphone setup.

a) Fixed Receiver: The fixed receiver consists of a host computer with an Ethernet connected Impinj Speedway R420 [27] and an USB/UART connected Nordic Semiconductor NRF51822 [24]. This setup is again described in Section III-A2.

b) Mobile Receiver: To test BLISP with a mobile reader, comparing to the fixed reader case, we have a prepared the following setup. Smartphone is selected as platform for mobile host, which consists of BLE and RFID reader. We developed an Android application (available upon request or via [25]) for the smartphone to scan the BLE channel and log all advertising data originating from the BLISP. As a smartphone-attachable RFID reader we selected the MTI MINI ME [35]. Based on the low level command set Application Programming Interface (API) provided by MTI, we log all inventory data.

Unfortunately, the MINI ME can only inventory WISP with fixed power supply up to a maximum range of 2 cm. To increase

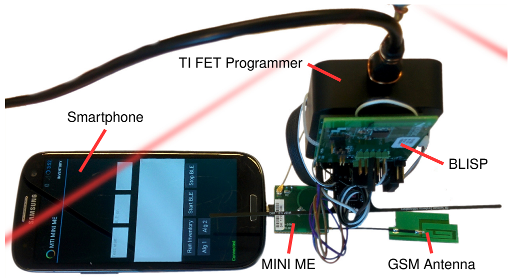


Fig. 4. **Mobile receiver BLISP test setup.** BLISP and TI FET programmer/power monitor are hanging from an overhead crane (the red diagonal wires) [37] as described in Section VI-A. MINI ME mobile RFID reader is shown without plastic housing, easing connection of a different antenna.

the inventory range of MINI ME, we replace the embedded antenna with a 2 dBi GSM band omnidirectional antenna [36]. By replacing the antenna, the maximum range is extended to 10 cm. Table I shows parameters for the two reader platforms, while Fig. 4 shows the MINI ME reader with GSM antenna connected to a smartphone running our application.

B. BLISP Software Architecture

The WISP component of the BLISP software consists of 1700 lines of C code and 1900 lines of assembly code of which 600 lines C and 50 lines assembly were written in the BLISP development process. The remaining part is based upon [38]. The BLE element consists of a 500 line C coded program and the NRF51822's API. The fixed BLISP host currently consists of various Bash and Octave scripts with varying lengths. The mobile host consists of 750 lines of customized Java code.

1) Wireless Identification and Sensing Platform: Because of the low power requirements and therefore our preference for backscatter communication we choose to have WISP acting as master over BLE radio. Between the periodic sensing and transmission rounds WISP is put into a low power state.

For all following experiments WISP measures temperature and a timestamp since the startup[2]. The timestamp is included for evaluation purposes, as this value enables to evaluate the number of missing and/or duplicate packets. To ensure a constant data stream in case of radio switching the sensor data is periodically shared with the BLE radio as described in Section V-A3. The BLE radio and the WISP are both set to have 12 Byte payload per message and ten messages are combined into a single transmission. As the temperature data combined with the timestamp only uses 4 Byte the message is padded with 8 Byte of constant data.

Because of incompatibilities between WISP and the MINI ME RFID reader used for the mobile host experiments the EPC C1G2 `tag select` mechanism [31, Sec. 6.3.2.3] is disabled for all fixed and mobile reader experiments.

2) Bluetooth Low Energy: BLE module (as decribed in Section III-A2a) is programmed as slave under WISP. As described in Section V-A3 the BLE radio is periodically awaken by the WISP to receive new data. When not wirelessly

[2]Other possible sensors are the accelerometer, already available on WISP, or any other (low power) electronic sensor.

Algorithm 1 BLISP Control Protocol

$x \leftarrow$ Maximum backoff window, see Section V-B3a
each PERIOD$_n$ **do**
  $a \leftarrow$ #ACK$_{n-1}$ ▷ Received ACKs
  $r \leftarrow$ #FRAME$_{n-1}$ ▷ Frames planned to transmit
  WISP$_{ok} \leftarrow (a = r)$ ▷ Expect ACK for each frame
  if WISP$_{ok}$ **then**
    backoff $\leftarrow 0$ ▷ No backoff on success
  if $0 =$ backoff **then** ▷ Is (re)try slot?
    WISP$_{TX} \leftarrow$ true ▷ Transmit using WISP
    if $\neg$WISP$_{ok}$ **then**
      backoff $\leftarrow \mathcal{U}(0, x)$ ▷ New uniformly random backoff
  else
    WISP$_{TX} \leftarrow$ false ▷ Not transmit using WISP
    backoff $\leftarrow$ backoff $- 1$ ▷ Shift backoff
  BLE$_{TX} \leftarrow \neg$WISP$_{ok}$ ▷ Use BLE if not use WISP

transmitting nor receiving (UART) data from WISP BLE module is put into a low power sleeping state.

3) Radio Switching: The software implements feed-forward channel estimation as proposed in Section IV-B. The circumstances and environmental influences affecting the RF performance of the WISP might change in a very irregular and most likely unpredictable way. We therefore propose and evaluate two switching approaches.

a) Random ($< x$): Making the switching mechanism depend on past results will decrease the number of unnecessary backscatter channel evaluations, thereby reducing overhead and improving energy efficiency. Because we assume the environment to have random unpredictable behavior we opt that it does not make sense to include a sophisticated self-learning algorithm. Our *random backoff* approach implements an ALOHA-inspired random backoff window with a maximum value of x. A low value of x will make the system more responsive while a high value will make the system more stable in the long run. A pseudo-code representation of this switching algorithm in shown in Algorithm 1.

b) Naïve: Limiting the maximum random value to zero will generate a constant as-short-as-possible backoff window resulting in the *naïve* approach. This approach (used as a reference) assures that we use WISP as much as possible which increases energy efficiency. At the same time, checking a perpetually broken WISP communication channel induces an overhead compared to other maximum backoff window sizes.

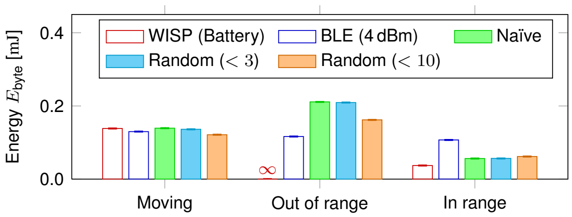
VI. Experimental Evaluation

To test the performance of BLISP we executed the following experiments measuring both goodput and energy consumption.

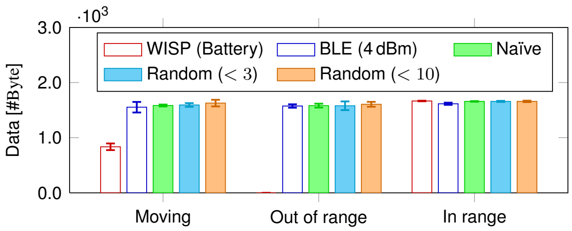
A. Experiment Setup

Our experimental setup consists of hardware components and methodologies for replicable and traceable measurements. For this test the BLISP (built as described in Section V-A) was running software as described in Section V-B.

1) Hardware: The measurement and evaluation setup we use for these experiments is based on the setup described in Section III-A2. In addition we use an automatic three-dimensional positioning crane [37] situated in a lab environment to automate the experiments involving a mobile BLISP.

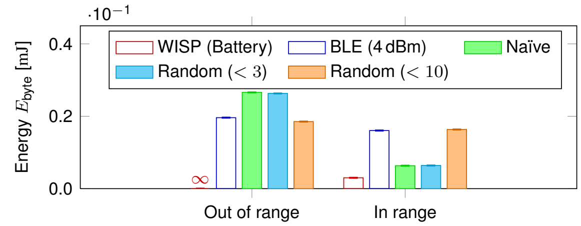


(a) Energy per byte comparison for all setups in different scenarios

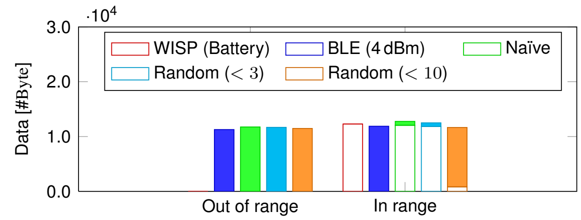


(b) Number of received messages for all setups in different scenarios

Fig. 5. **Results of the WISP, BLE and BLISP evaluation using Impinj R420 RFID reader.** Because of WISP not being able to transmit data in the long range, see Fig. 5(b), effectively wasting energy, the energy per byte is infinite for this situation, see Fig. 5(a). We show the only WISP, only BLE, naïve BLISP and random BLISP for random backoff windows up to three and ten slots. These experiments have been normalized to *unique* messages eliminating messages transmitted by both radios around switching moments.



(a) Energy per byte comparison for all setups in different scenarios



(b) Received messages per radio (BLE or WISP). Note: dark (top) part of bars—BLE messages, light (bottom) part—WISP messages

Fig. 6. **Results of the WISP, BLE and BLISP evaluation using MiniMe RFID reader.** Again, in the long range the MINI ME reader is not able to receive data transmitted by the WISP. Fig. 6(b) shows the distribution of received messages per radio for completeness of the illustration. Because of the limited logging capabilities on the smartphone the number of messages is not normalized to number of unique messages.

2) Replicability: According to Fig. 1 wireless radios have two main ranges of operation: (i) within the first range most of the packets get received and therefore the energy per byte ratio stays rather constant, (ii) within the second range almost no packets are received and the energy spend on transmitting a byte therefore increases drastically. For the BLISP performance tests we limit the transmission power and sensitivity of RFID reader and define two static positions, one in WISP-range and one outside WISP-range. The experiments were performed by placing the BLISP in the in-range spot, placing the BLISP in the out-range spot, and alternating the BLISP location between the in- and out-range positions on a predefined constant time interval (10 s). The BLE radio was in range for all experiments, otherwise the system would fail according to Corollary 2. The time duration for each experiment was 2 min and each experiment was repeated five times. We run baseline experiments with a battery powered WISP and a BLE radio transmitting at 4 dBm as used in Section III-A.

3) Data Collection: In experiments we log the number of received packets for RFID and BLE receivers. The power consumption is measured by the programmer interface using the EnergyTrace platform[3] [39]. Due to random startup delays of each platform, we match the start and stop of an experiment by asynchronously starting all platforms and logging their state after a fixed (empirically found) delay of 3 s.

B. Static RFID Reader Experiment

Measurements of energy per byte and transferred data, are shown in Fig. 5(a) and Fig. 5(b), respectively. Due to normalization to unique messages, the values in Fig. 5(a) are around ten times larger than the ones shown in Fig. 1.

Our experiments show that BLISP increases goodput almost infinitely in the long range compared to WISP (see Lemma 1) while not severely increasing power consumption over WISP in the short range. On the other hand BLISP almost halves energy consumption in the short range compared to a normal BLE radio while for Random ($x < 10$) increasing energy consumption by ≈25% on the long range. For the remaining two switching methods this difference is much larger. This is presumably caused by the amount of unneeded channel sensing operations and the overhead of redundant micro-controllers. As we add a mobility to the experiment we see WISP loosing a share of messages corresponding to the relative out of range time, this increases the energy per byte to the same level as the active BLE radio which is able to transfer data in all positions. The combined system cannot be more energy efficient than the most efficient radio for a certain position (see Corollary 3).

For an uniformly distributes in-/out-range mobility pattern the energy profit the BLISP has over the BLE radio in short range and the energy cost in the long range zero out. BLISP improves energy efficiency and throughput for situations in which the WISP can be used for half of the time.

C. Mobile RFID Reader Experiment

The experiment setup parameters on the BLISP side is the same as using fixed RFID reader in Section VI-A. The detail setup parameters of mobile data aggregator are as in Table I.

Results for the mobile host experiments as shown in Fig. 6 show comparable results among WISP, BLE and BLISP compared with fixed reader experiments from Section VI-B. The relative improvement from BLE to WISP and *naïve*-BLISP using a mobile reader is even larger while in-range. This

[3]Because of the limited API for the EnergyTrace platform we use synchronously timed screen shots and Optical Character Recognition (OCR) to log the energy measurements for experiments using the EnergyTrace.

relative improvement is mainly because the performance of the smartphone's BLE module has worse performance than the NRF51822 receiver. Interestingly, for in-range measurements, a large backoff window shows worse performance than the *naïve* and small backoff experiments. We suspect that this is caused by the hardware limitation of MINI ME. Based on our experiments, the MINI ME reader has trouble with rapidly moving, or only shortly available, RFID tags. Fortunately, the BLISP algorithm detects the failing RFID reader and correctly enables the BLE radio which results in continuous data availability.

VII. Limitations and Future Work

We list the limitations and action items for future work related to hybrid active/passive radio platforms:

1) **Improving platform switching mechanism:** Non-predictable mobility patterns require further research on learning mechanism to select the best backoff parameter x of Algorithm 1, or the complete redesign thereof.
2) **Reducing micro-controller overhead:** The current BLISP is built using two separate radio modules and therefore two micro-controllers. One micro-controller is a better approach, reducing energy consumption of BLISP.
3) **Extending to beyond two radio platforms:** By Corollary 2 and Corollary 3 adding radios with heterogenous characteristics to a hybrid system will increase the performance of BLISP, requiring research on radio selection.

VIII. Conclusion

In this paper we design, implement, and evaluate a hybrid radio platform composed of Wireless Identification and Sensing Platform (WISP) and Bluetooth Low Energy (BLE), denoted as BLISP. Through experiments we show that BLISP, in situations in which this hybrid platform stays within the reception region of the lowest power radio, i.e. WISP, the energy efficiency is improved compared to BLE. At the same time the reliability of BLISP is larger than the reliability of WISP alone when BLISP moves frequently away from the RFID reader range.

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