Receiver-Sensitivity Control for Energy-Efficient IoT Networks

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***Abstract*—To increase energy efficiency of receiver-dominated nodes in IoT networks, we introduce Receiver-Sensitivity Control (RSC). RSC enables a trade-off between communication range and reception efforts. This trade-off is achieved through multiple receiver-sensitivity levels that can be adjusted at run time. The receiver can operate on lower sensitivity levels with reduced power consumption and conserve energy if the received signal quality is sufficiently high or otherwise use higher sensitivity levels to avoid packet re-transmissions. We evaluate the technique in a simulation of a realistic network scenario. The results show substantial energy savings of about 10-20% for better-than-worst-case channel conditions.**

***Index Terms*—Low power, Circuit design, IoT, Receiver design, Adjustable sensitivity.**

I. Motivtation and Related Work

Many emerging network applications in the context of the Internet-of-Things (IoT) have rigid energy constraints that introduce new low-energy network design challenges. Some wireless sensor networks require sensor nodes to continuously send sufficiently reliable data for years before they run out of energy. To enable such applications, the energy consumption of the nodes needs to be conserved whenever possible. Wireless transmission is often a dominant source of energy consumption [1]. To reduce the energy consumption per transferred byte, packet transmission and processing efforts need to be just enough for a sufficiently reliable signal recovery at the receiver side. Reliability can be achieved with channel coding [2] that corrects errors caused by poor signal-to-noise ratio and, hence, reduces packet re-transmissions. Transmission-Power Control (TPC) covers ways for an IoT node to transmit a packet with a transmission power just high enough to satisfy the packet reception ratio requirements [3]. The CSMA/CA protocol [4] allows the data sending nodes to sleep most of the time and only wake up for the data transmission, while any receiver is always awake waiting for possible packet receptions. The counterpart of CSMA/CA-like protocols for energy-efficient reception are receiver duty cycling techniques such as discontinuous reception DRX from 3GPP [5] or Coordinated Sampled Listening (CSL) and Low Power Listening (LPL) from IEEE 802.15.4 [4], [6]. These techniques allow the receiving nodes to sleep most of the time through periodic short channel sampling and detection of an incoming packet.

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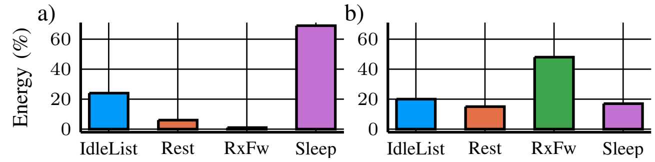

Fig. 1. Energy breakdown of relay nodes measured in [7]: a) node with low relay traffic; and b) node with high relay traffic. Reception energy covers IdleList and half of RxFw, about 44% in b) and about 25% in a).

However, despite effective LPL techniques, many emerging IoT applications are still limited by low-power wireless receiver-dominated nodes such as actuator nodes or packet-relay nodes in a multi-hop network that spend a significant amount of energy on synchronization, packet reception and recovery. In contrast to sensor nodes, actuator nodes or relay nodes receive at least as many packets as they transmit. The energy breakdown of two relay nodes in an environmental monitoring application is illustrated in Fig. 1 [7]. Half of the packet forwarding energy (RxFw) and all the listening energy (IdleList) is spent in reception mode, which sums to 44% of the energy consumption for the high-traffic node. A reduction of reception energy significantly increases battery life time and hence decreases the network maintenance costs.

This brief proposes Receiver-Sensitivity Control (RSC) as an energy-reduction technique through configurable receiver-sensitivity adjustment. RSC is a counterpart to TPC and complements other energy-efficiency approaches such as channel coding and duty cycling. While TPC reduces the power of transmission, RSC reduces the power of reception with a similar impact on the communication range. The implementation of an analog front end and a digital baseband enabling RSC are described in [8] and [9], respectively. These papers show receiver implementations with adjustable circuit-level parameters that provide a sensitivity-power trade-off required for RSC. To show the efficacy of RSC, we analyze the environmental monitoring setup from [7] in OMNeT++ [10] and show energy savings of about 10-20% per successfully received byte for better-than-worst-case channel conditions, where the specific savings depend on the network setup.

The contributions of this work are the following:

- Introduction and analysis of receiver sensitivity as an adjustable network-level parameter.
- Evaluation of the proposed approach in a realistic network scenario for environmental monitoring.

The most important insights of this work are the following:

- Circuit-level receiver design provides opportunities to scale down power consumption at the cost of degradation of received signal quality. Through cross-layer design, the quality degradation can be compensated at network-level while preserving energy savings. RSC creates a run-time configurable link between those circuit-level power scaling techniques and network-level quality compensation.
- The opportunity for RSC effectively arises with emerging short-range low-rate low-power networks, with receivers consuming a significant amount of power. In such networks, the total improvement through TPC is limited by the receiver power consumption. RSC complements TPC. RSC can be implemented locally without the need for coordination between nodes because the signal quality can be measured locally at the receiver.

RSC is presented in Section II. The network-level evaluation of RSC is presented in Section III. Section IV concludes.

II. Sensitivity-Power Trade-Off for IEEE 802.15.4 Conformant Receivers

To reduce energy consumption of nodes with a dominant receiver operation, we propose to scale receiver sensitivity for power. The concept is illustrated in Fig. 2. TPC allows adjustment of transmission power $P_{tx,rf}$ at network level through the MicroController Unit (MCU). TPC and communication protocols such as CSMA/CA [4] enable energy-efficient transmission. Energy efficiency of the receiver is addressed through synchronization routines and beaconing by protocols such as TSCH [4], LPL [6], and CSL as specified in [4]. In those protocols, the receiver only samples the channel at specified moments in time for incoming packets and goes to sleep mode if none are detected. To avoid missing packets, LPL/CSL-based protocols specify dedicated preambles that enable packet detection by the receiver. The proposed RSC reduces energy consumption of reception by trading off receiver power consumption for the sensitivity R_{sens} at network level. It is therefore complementary to LPL/CSL.

A. Sensitivity Definition

Sensitivity R_{sens} is the minimum power of the received signal under which the signal can be received with tolerable Packet Error Rate (PER). It depends on the minimum tolerable signal to noise ratio $(\frac{S}{N})_{min}$, and is defined by (1) [11].

$$R_{sens} = (\frac{S}{N})_{min} \times BW \times kT \times NF. \quad (1)$$

BW is the bandwidth of the receiver, kT is the thermal noise power, and NF is the noise figure specifying the added noise by the analog components of the receiver. For example, the maximum PER specified by IEEE 802.15.4 for O-QPSK radio is 1% with $R_{sens} <= -85$ dBm [4].

At the network level, the ratio of the sending node's transmission power ($P_{tx,rf}$) and the receiving node's sensitivity (R_{sens}) defines the maximal signal path loss with tolerable PER. IEEE 802.15.4-conformant nodes have several levels of transmission power e.g., from 10 dBm down to -20 dBm.

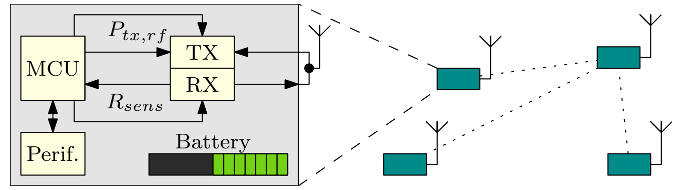

Fig. 2. An RSC-enabled IoT node. To conserve energy, the receiver can reduce sensitivity R_{sens} and operate on lower power levels.

B. Possibilities for a Sensitivity-Power Trade-off

If the current signal path loss towards a receiver allows reduction of sensitivity R_{sens}, then the excessive sensitivity can be traded for power in the Low Noise Amplifier (LNA), the Analog to Digital Converter (ADC), and the Digital BaseBand processor (DBB). This can be achieved by making circuit-level parameters adjustable (e.g., biasing voltage, digital resolution, sampling rate).

The LNA is the first element in the receiver chain after the antenna, which fundamentally defines the achievable sensitivity. With an adjustable LNA, the noise figure NF in (1) can be traded for power. This is effectively demonstrated in [8] by using different back biasing voltages.

The ADC is another key receiver element that gives further power-sensitivity trade-offs. With ADC, the sensitivity can be traded for power through variable sampling frequency and through the Effective Number Of Bits ($ENOB$) being used. These two factors impact NF by adding sampling and quantization noise. Reduction of $ENOB$ by only one bit, for instance, can reduce the ADC power consumption by 50% at the cost of worsening R_{sens} by approximately 6 dB [12]. This trade-off can be implemented through flexible ADC architectures such as reported in [13].

R_{sens} also depends on the signal processing in the DBB. The first component of R_{sens}, $(\frac{S}{N})_{min}$, can be traded for power savings in the DBB using adequate computing as shown in [9]. The digital filters can be designed in several by-passable stages, which can be shut down and/or clock gated for power savings. Furthermore, demodulation schemes can be relaxed through reduction of the signal bit-width and clock frequency. Finally, different decoding schemes expose different power-error correction trade-offs. For example, a Viterbi decoder with flexible error-correction vs. power trade-off is presented in [2].

The circuit-level implementation costs to realize adjustable sensitivity and the network- and circuit-level adjustment overhead may limit the efficiency of the proposed RSC in very dynamic environments. However, the implementation costs for the mentioned circuit-level techniques are very low. For applications such as environmental monitoring or precision agriculture, change is infrequent and adjustment overhead is negligible.

C. Possibilities for Sensitivity-Power Adjustment

To quantify the path loss between transmitter and receiver, channel-quality estimation is necessary. Such functionality is available at circuit level, e.g., via a symbol correlation metric or link quality indicator. This circuit-level functionality can be

TABLE I
TWO RECEIVER MODES FOR A POWER-SENSITIVITY TRADE-OFF

Mode	Power	$R_{sens}/P_{tx,rf}$	Rel. Savings (%)
RX_{HighS}	53 mW	-95 dBm	0
RX_{LowS}	34 mW	-85 dBm	35
TX_{HighP}	47 mW	0 dBm	0
TX_{LowP}	30 mW	-10 dBm	35

connected directly to adjustable receiver parts, building a self-regulating feedback loop. Alternatively, the adjustment can be performed on network level where more information about the network quality of service and the channel is available. RSC refers to such network-level adjustment techniques. RSC avoids a continuous circuit-level sense-and-adapt operation of which the impact at network level is not clear.

At the network level, the path loss can be indirectly estimated from Packet Reception Ratio (PRR) or Received Signal Strength Indicator (RSSI). Based on such estimations, it can be decided what sensitivity level to use. In principle, a simple thresholding mechanism suffices and no coordination between nodes is necessary. The estimations and the decision can be local to the receiver node.

RSC enables the network designer to adjust not only the transmitter-side parameters but also the receiver parameters, resulting in more flexible deployment time and run-time adaptive network configurations. Energy in transmitter nodes can be traded for energy in receiver nodes, by increasing transmission power on the transmitter side to improve signal to noise ratio on the receiver side, allowing the receiver to reduce R_{sens} and hence power consumption.

III. Network-Level Analysis

To show the efficacy of RSC, a case study is modeled and simulated in the OMNeT++ network simulator [10]. It is our aim to compare RSC with TPC.

As IoT communication protocol, we initially choose IEEE 802.15.4 [4] in the non-beacon enabled mode with the LPL technique from BMAC [6]. We consider the MICAz node [14] as the nodes for our case study. The MICAz node has two transmission (TX) power modes, $P_{tx,rf} = 0$ dBm and $P_{tx,rf} = -10$ dBm, with power consumption values as given in Table I. The values for RX_{HighS}, TX_{HighP}, and TX_{LowP} are taken from the MICAz datasheet [14]. For comparison between TPC and the proposed RSC, we assume a second sensitivity (RX) mode, RX_{LowS}, which can be realized from the circuit-level techniques identified in the previous section. The RX_{LowS} mode mirrors TX_{LowP} by providing the same reduction in sensitivity and the same relative reduction in power consumption.

To complete the simulation setup, the monitoring scenario reported in [7] is recreated in the simulator. The network configuration is shown in Fig. 3. In the reported scenario, all nodes collect environment information and send this information to sink node 0. Every node transmits the sensed data once every 15 minutes. If a direct link to the sink is not possible, the packet is relayed through nodes that are closer to the sink. We use the basic transmission loss model with LogShadowing from the ITU P.1411 [15] recommendation in the simulations. According to that model, the path loss can vary by 10 dB

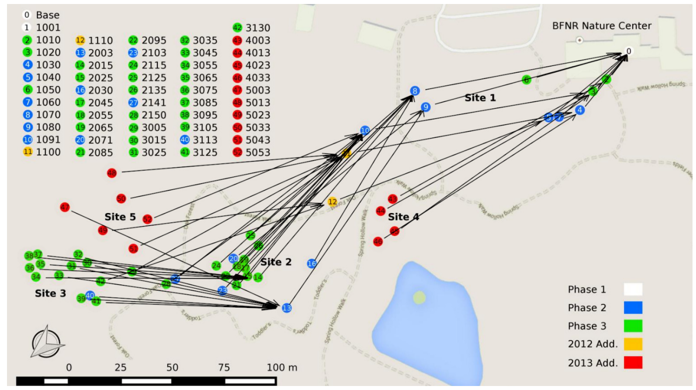

Fig. 3. Experimental network setup in the OMNeT++ simulator reported in [7]. The fixed routing, used in the evaluation, is shown with black arrows.

depending on, for example, weather conditions or whether or not there are leaves on trees. To account for the worst-case conditions, we fix the network routing (as shown in Fig. 3) to deliver packets with an acceptable PER below 0.01% with full transmission power $P_{tx,rf} = 0$ dBm and full receiver sensitivity $R_{sens} = -95$ dBm even when the path loss is degraded by 10 dB.

With our simulations, we analyze the network for better-than-worst-case conditions to show the energy-saving potential during those periods. The background noise is set to -95 dBm. We simulate and analyze both TPC and RSC separately while readjusting the LPL parameters for minimal energy per byte. The packet payload is 20 Bytes. $P_{tx,rf}$ and R_{sens} in TPC and RSC, respectively, are reduced by 10 dB, running the TX_{LowP} and RX_{LowS} modes shown in Table I. All other parameters in the simulations are set as reported in [7]. As a comparison metric, we use overall energy per successfully transferred byte of information from a sensor node to the sink on average. We compare the RSC and TPC results against a baseline network with maximal sensitivity and transmission power.

We run the network configuration for one day. We exclude energy of the sink node because that node is likely connected to the power grid. The resulting energy breakdown is illustrated in Fig. 4. The main cause of the high amount of listening energy is the overhearing effect. A packet sent to one node is also received by other nodes and can only be discarded after the packet is completely received and decoded, because only then the destination address is known. That effect is known and reported as a shortcoming of the BMAC LPL mechanism in [6]. Because of the dominant reception energy due to overhearing, the energy savings with TPC are only around 7%. The energy savings with RSC are about 20%. Note that packet reception at the sink is not affected, because

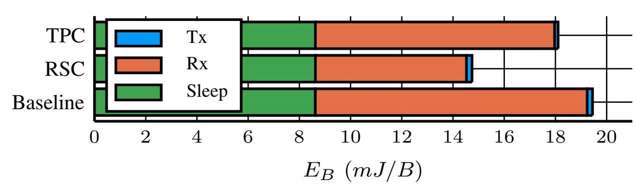

Fig. 4. The energy per byte with LPL for three configurations: Baseline with maximum transmission power and reception sensitivity, TPC with reduced transmission power, RSC with reduced sensitivity.

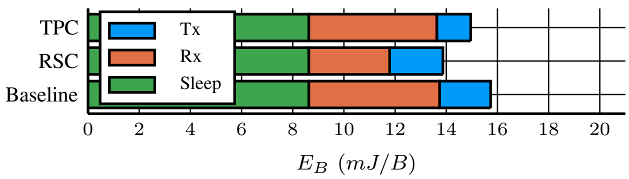

Fig. 5. The energy per byte with CSL for three configurations: Baseline with maximum transmission power and reception sensitivity, TPC with reduced transmission power, RSC with reduced sensitivity.

of the better-than-worst-case channel conditions assumed for this setup.

An alternative to BMAC is CSL as specified in the IEEE 802.15.4 standard. CSL uses a train of wake-up packets instead of a preamble. Once the receiver wakes up, and receives the wake-up packet, the address of the sender is known, reducing the overhearing overhead. However, to reliably receive the wake-up packet, the receiver has to listen to the channel longer than in LPL after every wake-up. The energy per byte for TPC and RSC with the CSL protocol is presented in Fig. 5. Compared to the baseline, 5% and 11% energy savings are obtained for TPC and RSC, respectively.

An interesting observation is that the baseline configuration with CSL (maximum transmission power and high receiver sensitivity) has approximately the same energy consumption as LPL with RSC (i.e., low receiver sensitivity). However, the receiver sampling period used in LPL is significantly shorter than in CSL. For CSL, the period is 1.5 seconds, while for LPL it is 50 milliseconds. Assuming the receiver wake-up time is evenly distributed over a sampling period, this difference results in the network latency for CSL to be 15 times higher than for LPL on average. So CSL and LPL provide a trade-off between energy efficiency and latency.

Another interesting feature of RSC is increased robustness against interference. After increase of the background noise from -95 dBm to -90 dBm, TPC with decreased transmission power fails to maintain the required PRR and dramatically loses on energy efficiency because of an increased number of re-transmissions. However, RSC is not affected by the increased background noise. This is because TPC affects the ratio between interference power and received signal power, while RSC does not.

We may conclude that the impact of reduced reception power in the simulated scenario is significant. It is moreover larger than the savings that can be obtained through TPC, with the additional advantage that RSC can be implemented locally in a node without the need to align with other nodes. The obtained savings are due to the presence of receiver-dominated (relay) nodes in the network, absence of wake-up radio or other extra low-power listening circuits, a low packet transmission rate of 1 packet per 15 minutes, and drawbacks of the LPL/CSL-CSMA/CA combination. The concrete savings that may be obtained with RSC depend on the network setup and the amount of time that parts of the network operate in better-than-worst-case conditions. But the results show that RSC is a useful additional tool to further improve the energy efficiency of IoT networks.

The energy savings can be further improved through the combination of TPC and RSC. In our simulations, we applied a globally uniform network adjustment. Node-position-specific differences in path loss are not addressed. To maximally exploit the saving potential of combined TPC and RSC, new routing algorithms are needed that are aware of adjustable sensitivity in general and link-specific transmission-power and receiver-sensitivity adjustment in particular. These topics are interesting directions for further work.

IV. Conclusion

With this letter, we advocate Receiver-Sensitivity Control (RSC) as a network-level technique to improve energy efficiency of IoT networks. An RSC-capable design is able to change and trade off its receiver sensitivity against power consumption at run-time. We identify the technologies that make the design of such a receiver possible and show benefits of RSC through OMNeT++ network simulations. The results show that network-level configurable sensitivity improves energy efficiency in a realistic environmental monitoring scenario by about 10-20%, depending on the network setup. The integration of RSC into energy-conservation mechanisms and energy-efficient adaptive routing apporaches would therefore result in further energy savings in IoT networks.

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