# Understanding the Impact of Circuit-Level Inaccuracy on Sensor Network Performance

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# ABSTRACT

Energy efficiency is of paramount importance in designing lowpower wireless sensor nodes. Approximate computing is a new circuit-level technique for reducing power consumption. However, the gain in power by applying this technique is achieved at the cost of computational errors. The impact of such inaccuracies in the circuit level of a radio transceiver chip on the performance of Wireless Sensor Networks (WSNs) has not yet been explored. The applicability of such low-power chip design techniques depends on the overall energy gain and their impact on the network performance. In this paper, we analyze various inaccuracy fields in a radio chip, and quantify their impact on the network performance, in terms of packet latency, goodput, and energy per bit. The analysis is supported by extensive network simulations. The outcome can be used to investigate in which WSN application scenarios such power reduction techniques at circuit level can be applied, given the network performance and energy consumption requirements.

# Keywords

QoS provisioning in wireless and mobile networks, Sensor and actuator networks, approximate computing.

# 1 Introduction

Wireless Sensor Networks (WSNs) are evolving dramatically, finding applications in many new fields such as medical diagnosis, automotive, and agriculture. For example, body area sensor networks make it possible for medical specialists to track the patients' state without constraining their movements. The less energy is consumed by a sensor node, the more application opportunities arise. The nodes with sub milliwatt average power dissipation are able to operate for years on a single small battery. Furthermore, they may exploit a kind of environmental energy scavenging techniques to further increase their lifetime without the need for any human intervention.

To achieve this ultra-low power operation goal, the network design needs optimizations on every abstraction level. The

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computational load of the nodes needs to be reduced to the minimum, but still satisfy the specific application's performance demands. There is considerable effort in literature on effective energy saving techniques on different aspects of WSNs. On the network level, energy savings are considered in all layers of the protocol stack mainly by optimizing the radio activities for acceptable throughput and communication reliability. The standard technologies for low-power WSNs (e.g., the IEEE 802.15.4 [1]) combine the most energy efficient optimization techniques with sufficient flexibility for diverse applications.

Significant power savings are also achieved through optimizations at circuit level while designing ultra-low power radio transceiver chips. The iterative improvement of the IEEE 802.15.4 conformant transceivers started with the first fully integrated transceiver designs such as those described in [1]. An average power consumption below six milliwatts was achieved in [2] due to technology scaling, partial offloading of the signal processing from analog to digital domain as well as smart energy efficient control of analog components.

Current advancements in designing low-power radio chips and efficient protocol stacks are not yet enough to satisfy the dreams of years of operation for wireless sensor nodes. Thus, new power reduction techniques are needed. Recently, diverse power reduction techniques, called approximate computing [3], are proposed that effectively trade circuit level reliability and accuracy for power or energy. The paradigms of approximate computing suggest using inexact circuits and algorithms, which are faster and more energy efficient but do not always have a fully precise output. Although these techniques have shown their effectiveness in domains such as image and video processing [4], their applicability to WSN transceiver design is not yet explored. The circuit level inaccuracies caused by applying an approximate computing technique affect the performance of the higher levels. For instance, a computational error in scheduling may cause transmission in an already occupied time frame leading to collisions. An error in channel assessment may cause a collision if the busy channel is falsely estimated. The impact of such circuitlevel errors is not straightforward and needs a careful investigation. For example, a wrong channel assessment may happen also in case of accurate transmitter implementation. Thus, circuit level inaccuracies may be masked by the natural inaccuracies, without affecting the network performance. Moreover, collisions or data losses that may happen due to an inaccurate transceiver increase the need for packet retransmissions, leading to higher energy consumption. Thus, the power savings at circuit-level may be wasted by extra communications imposed to the network level. To decide whether such power reduction techniques are in the end beneficial, we

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Fig. 1 General architecture of a radio transceiver.

need to understand and quantify their impact on the network performance.

This work focuses on identification of circuit-level inaccuracies, the errors that they may cause at the network level, and analysis of their impact on the network performance. The circuit level inaccuracies may affect the channel assessment or bit stream processing. They may further cause some errors in transmission scheduling or packet reception. In all cases, their impact depends on the channel conditions, network state, and its configuration. In this paper, we first analyze the impact of circuit-level inaccuracies on the performance of networks in terms of latency, goodput, and energy per bit. Then we investigate the performance metrics using extensive network simulations while injecting errors. Without loss of generality, this paper focuses on a star network running an IEEE 802.15.4 conformant unslotted CSMA/CA protocol. The results of this analysis give a better insight into the relations between circuit-level inaccuracies and network performance, and enable better understanding and definition of the Quality-of-Service (QoS) metrics applied to inaccurate transceiver implementation.

The rest of the paper is organized as follows. First, the concept of approximate computing and the corresponding circuit-level inaccuracies are briefly introduced in Section 2. Then, the impact of inaccuracies is quantified in Section 3. The network-level metrics of interest are also defined. The errors in different blocks of the transceiver are identified, and their impact is analyzed in Section 4. Finally, the analysis results are summarized and discussed in Section 5.

### 2 Circuit-Level Inaccuracy

The focus of this work is on circuit-level inaccuracy caused by emerging techniques like approximate computing paradigm [3], which trade accuracy for power. The approximate computing methodologies propose inaccurate operations, which are less power hungry, but expose errors that are still tolerable on application level. The authors of [5] are pioneering the approximate computing in the field of image filters. The filter works with 2-bit multipliers that have one incorrect output for one specific input combination (3 times 3). The flipping output bits for this combination allow to significantly simplify the multiplier circuit and save circuit power, area, and computational delay. The designed filter is demonstrated to process the images with satisfying quality, and significantly lower power consumption compared to conventional filters.

The idea is theoretically applicable to the radio transceivers to reduce their power consumption. However, the relation between the approximation errors at circuit-level and network performance is not straightforward and needs to be investigated in detail. Generally, the approximation can be introduced in different network operations of a radio transceiver. On the network level, the operations can be categorized into three types as follows:

- packet transfer (RX and TX);
- channel analysis;
- node synchronization.

Packet transfer operations correspond to the actual packet transmission and reception, while channel analysis and node synchronization ensure the transfer success. The general operational schematic of a typical WSN transceiver is illustrated in Fig. 1. During a packet transfer, the data payload is encapsulated into a packet, encoded, modulated, mounted on a carrier frequency with a mixer, and amplified to a desired power level with a Power Amplifier (PA). The signal is propagated by an antenna. The propagated waves are captured at a receiver, amplified by Low Noise Amplifier (LNA) and converted to the baseband with a mixer, filtered, demodulated, and decoded by the receiver radios in the communication range of the transmitter. Approximations can be introduced to the signal filtering and (de)modulation blocks since they are among the most power expensive operations during the transfer. Channel analysis operations provide channel state information for a node with the intention to schedule packet transmission or to synchronize with an incoming packet. Channel analysis and node synchronization operations also involve heavy computations and demand significant amounts of resources and, hence, form a potential approximation target. The approximations can be introduced into Preamble Detection (PD) and Clear Channel Assessment (CCA) blocks in a radio transceiver.

Approximation errors during different network operations have different impact on the network behavior and performance. Errors in the receiver's filter or demodulator degrade effective Signal to Noise Ratio (SNR), leading to higher Bit Error Rate (BER). This eventually can lead to a higher packet drop rate. Depending on the network configuration, a packet loss is directly connected to data losses or longer transmission delay due to retransmissions. Thus, energy for transmission at source nodes and for reception at receiver nodes is wasted. However, the demodulator and decoder provide error resiliency, which is usually needed to deal with worst-case channel noise. This robustness might be enough to recover the inaccurately filtered signal without bit errors.

The impact of errors in preamble detection is different. The outcome of the operation is a binary decision which can be wrong in two ways: 1) The incoming preamble is not detected and ignored (detection error); 2) A positive preamble detection is reported without any incoming preamble (false detection). A preamble detection error also leads to a packet drop. However,

using a smart listening mechanism, only the transmitter energy is wasted (the receiver may sleep after a timeout if no preamble is detected). False detection may cause more damage, because the full reception path remains active and synchronizes to a misaligned or non-existent packet. However, the circuit inaccuracy is not the only source for a false detection and it can be masked by other natural causes like inability to wake up the receiver at the right time due to not synchronized clocks at transmitter and receiver.

The CCA block has a binary decision outcome as well and accordingly, has two possible error types with different consequences. A detection error at CCA leads to a packet collision or transmission error in presence of strong interference. A CCA false detection causes unnecessary back offs in the transmitter node, resulting in a higher latency and eventually even a packet drop because of the limited number of allowed back-offs or packet buffer overflow in the transmitter. However, the real impact on the network performance depends on the environment and the network situation. Even with an exact CCA computation, collisions can still happen due to simultaneous channel sensing by two transmitter nodes in a neighborhood. These aspects show that the impact of approximate circuits on the network performance is not straightforward.

To investigate the relation between circuit-level inaccuracy and network-level performance, in the following sections, the performance metrics are defined and connected to the circuit-level faults.

# 3 Quantifying the Impact of Inaccuracy

### 3.1 Approach

To investigate the impact of circuit-level inaccuracy on network performance, an operational state-based network behavioral model is used. The operational states and state transitions of the model are defined in such a way, that the network performance metrics can be computed considering the faults in the underlying computations. In the following, we define the operational states of the model, the state transitions, and the way this model is used in our investigation. Note that the model itself is not the main contribution of this paper; it is merely an abstraction of transceiver activities which is detailed enough to describe the circuit inaccuracy related mechanics. The parameters of this model are calculated using OMNet++ [6] simulations. Using this behavioral model, the network behavior is simulated with insertion of different inaccurate computing effects. The results of the simulations are used for computing the network performance metrics. In particular, during the simulation, estimated time stamps of specific events and time durations of the defined states as well as accumulated total number of received and sent packets are used for calculation of performance metrics. This information helps the radio chip designers to understand the QoS penalties that their approximation technique at each block of the transceiver may cause. In turn, the results can determine if the power saving at circuit level using an approximation technique is beneficial in terms of the overall network performance and nodes' energy consumption.



Fig. 2 WSN node's operational state diagram.

This approach is general and applicable to most network configurations and protocols. In this paper, the approach is applied to an IEEE 802.15.4 conformant unslotted CSMA/CA protocol, as a showcase. As an example, the protocol is applied to 11 nodes in a star network topology (ten sensor nodes and one coordinator). The OMNet++ network simulator [6] provides an IEEE 802.15.4 conformant unslotted CSMA/CA based node model, which is similar to the defined operational state based model. Hence the calculation of the needed time durations is straightforward. The sensor nodes are assumed to periodically generate enough data for a full-size packet transmission. Because the unslotted CSMA/CA protocol does not require node synchronization, the periodic data send requests from application level of the nodes are not aligned. For sufficient coverage of average network behavior, the alignment among the nodes is randomized and several repetitions of the simulation with different random patterns are performed to have statistically more reliable results. The inaccuracy is introduced through error insertion during the simulation of the behavioral model. For example, when the circuit calculation based decisions or state transitions are triggered, the introduced modifications allow to change the decision or transition randomly, but with controlled probability. Finally, the network performance metrics are averaged over time and repetitions.

For definition of network performance, three performance metrics are used, 1) end-to-end latency (*L*), 2) the total throughput (*R*), and 3) averaged Energy per Bit ( $W_b$ ). For  $W_b$ , only the network level energy penalty is considered but not the circuit-level energy benefits of the inaccurate circuits. In this way, the complex cross layer performance vs. accuracy relation is structured. The investigations described in this paper give insight in the network level penalty for inaccurate computations on lower levels of abstraction. This information can be used as criteria for introduction of circuit level inaccuracy for better matching of the design performance and specific application demands or specifications of the accuracy constraints. As a demonstration of the potential benefits of the analysis, an inaccurate CCA circuit was designed according to the analysis discoveries and evaluated. The resulting energy benefits are shown in Section 4.5.

# 3.2 Behavioral Model of Wireless Nodes

The behavioral description of a typical wireless sensor node is expressed in a state-based model, as shown in Fig. 2. The states under consideration in this work are Reception State (RS), Transmission State (TS), channel Scanning State (SS), Idle State (IS), and Channel Sensing state (CS). In the RS state, the node is actively receiving, demodulating, and decoding an incoming packet. The channel scanning state is a state in which the node is waiting for an incoming packet. In this state, the preamble detection block is active. In many MAC protocols, before a packet transmission, the transmitter node first switches to the channel or carrier sensing state to assess the channel availability. If the channel is detected as busy, the node may wait until the channel becomes free. In the IS state, the main receiver and transmitter blocks are turned off and the transceiver conserves the energy until the next reception or transmission. The TS and RS states are marked green because those are the only ones which directly contribute to the delivery of the payload data.

Those two states are the most important states for goodput. SS, IS and CS operational states build an overhead which is necessary for synchronization and collision-free channel sharing. SS and CS states can be treated as an RS state in the analytical models because of their short duration and negligible difference in energy consumption compared to the RS state. However, the operations performed during SS and CS are functionally different, and significant as they ensure the success of actual data transfer performed in the TS and RS states. In the state-of-the-art WSNs with growing node numbers, channel occupation, and more rigorous energy constraints, the SS and CS states become significant and need to be treated separately. Furthermore, from many works such as wake-up radio [7] or low power listening [8], it is evident that the optimization of the SS and CS operations has considerable impact on the overall energy consumption. In the center of the diagram is the idle state. Ideally, in this state, only scheduling timers are on, and the rest of the transceiver is disabled. Hence, the transceiver saves energy in the idle state. Energy efficient MAC protocols ensure that the node stays in IS as long as possible.

The model is generic enough to be applied for various communication protocols. The difference is in the state transition conditions, which may be complex relating to a given communication protocol. If there is a pending packet to be sent, the Prepare-Transmission (PTX) transition is triggered, and the transceivers state is changed to CS. In the CS state, the transceiver analyses the channel and decides whether it is now an appropriate time for transmission of the packet. Depending on this decision, either the state transition Quit Transmission (QTX) occurs with which the transceiver backs off into IS, or transition Execute Transmission (ETX) is triggered, and the transceiver switches to the TS state. After the packet is transmitted in the TS state, the transceiver switches back to the energy conserving IS state via the Finish Transmission (FTX) state change. The node cannot receive an incoming packet unless it is in the SS state. Hence, the Prepare to Receive state transition to SS needs to be ensured at the right moment. If a node detects the incoming packet in SS, the Execute Reception (ERX) state transition is triggered. If the receiver is not able to detect the incoming packet after a time-out, it switches back into IS through the Quit Reception (QRX) state transition. After a successful packet reception, the Finish Reception (FRX) state transition is issued.

This model allows to introduce circuit level inaccuracy and investigate their effects. In case of failed preamble detection, for example, the QRX transition is triggered instead of ERX. Computational approximations in CS may cause QTX instead of ETX or vice-versa. This model is flexible enough to describe and simulate most state-of-the-art communication protocols. On the other hand, the model is detailed enough to extract network performance metrics from the simulation results.

#### **Network Level Performance Metrics** 3.3

The performance of a WSN is generally defined through three distinct metrics: transmission latency (L), goodput (R) and energy per bit  $(W_b)$ . In this paper, we consider the link layer latency which is the delay between the application layer send request time in the source node  $(t_{app,tx})$  and reception notification time in the receiver from the destination node  $(t_{app,rx})$ :

$$L = t_{app,rx} - t_{app,tx}.$$
 (1)

The goodput R is defined as the number of payload data bits  $B_{payload}$  successfully transmitted in a given time window T.

$$R = \frac{B_{payload}}{T} \tag{2}$$

where  $B_{payload}$  is the number of transmitted data bits in the network, and *T* stands for the time window under consideration. Note that the goodput is calculated on the network level, and is not averaged over the nodes. For WSN nodes which share the same channel, the overall network throughput is important. Energy per bit is defined similarly in Eqn. (3).

$$W_b = \frac{W}{B_{payload}} \tag{3}$$

where  $W_b$  is the energy consumed by all nodes for transmission of the given payload of  $B_{payload}$  bits.

For the calculation of the values, we use the operational state based model under the assumption that the energy consumption of the nodes in a given operational state is linearly scalable with time. For example, energy consumption of a node in reception state can be calculated using

$$W_{rx} = P_{rx} \cdot T_{rx},\tag{4}$$

with average power consumption in reception state  $P_{rx}$  and reception duration  $T_{rx}$ . Average power consumption of the node during signal reception can be calculated at circuit level while the duration of the reception can be computed based on network level simulations or analytical models. The energy spent in other operational states are calculated similarly. The total energy consumption of the network is then the sum of all operation-state wise calculated energy as shown in Eqn. (5).

$$W_{total} = \sum_{state} P_i \times T_i \tag{5}$$

With accumulated received data bits at every node, the energy per bit can be calculated using Equations (3) and (5).

$$W_{total,b} = \frac{\sum_{nodes, states} P_{i,j} \times T_{i,j}}{\sum_{nodes} B_{rx,payload}}$$
(6)

The  $(L, R, W_h)$  requirement depends on the application. Body area sensors, for instance, should be extremely small and not



Fig. 3 CSMA/CA procedure [9].

noticeable for the carrier. This fact implies low  $W_b$  requirement. The monitoring sensors have typically relaxed latency requirements but may demand high effective throughput (goodput). The actuator nodes need the payload to be delivered within a limited time window for their real-time performance. It is an essential task to provide the most adequate  $(L, R, W_b)$  combination for a specific application case. However, it is challenging to find an optimal  $(L, R, W_b)$  combination because the factors depend on specific implementations in the lower levels of abstraction.

# 4 Results

# 4.1 Network Configuration

We investigate the non-beacon enabled mode of the IEEE 802.15.4 standard protocol (unslotted CSMA/CA) as a demonstrational example. CSMA/CA is a simple but efficient collision avoidance procedure, which is based on a "listen-before-talk" principle. The mechanism is efficient in low-traffic networks because there is no beaconing or synchronization of nodes necessary. Moreover, the overhead due to collision avoidance is small. The procedure is illustrated in Fig. 3 [9]. Before a packet is transmitted, the transmitter node waits for a randomized amount of time and then performs a CCA to realize the current condition of the wireless channel. The randomized amount of time is defined in Eqn. (7).

$$T_{BO} = random(2^{BE} - 1) \tag{7}$$

 $T_{BO}$  is a uniformly random number with the maximal number of  $2^{BE} - 1$  time units. The time units as well as BE are defined by the IEEE 802.15.4 standard. In the case that the channel is estimated as idle, the node switches to its transmission mode and sends the packet (Success). In case of a busy channel, the node goes to a back-off routine in which the node waits for  $T_{BO}$  with increased BE and then repeats the process. *NB* is the counter of the back-offs. Every time CCA reports a busy channel, the randomized waiting time factor (*BE*) is adjusted for longer waiting periods (up to maximum size), and *NB* is incremented by one. When the channel is busy for a long time, *NB* may exceed

*macMaxCsmaBackoffs*. Then the MAC layer gives up, and notifies the upper layers in the protocol stack about the transmission failure.

Two investigation cases are described: 1) general non-beacon enabled mode of IEEE 802.15.4 with general inaccuracy in every relevant functional block as a case study, and 2) a concrete beneficial protocol implementation as a show case. For the first investigation case, the default protocol configuration is used (i.e., the macMaxBackoffs, macMinBe and macMaxBe parameters are set to 4, 3, and 5 respectively). The packet acknowledgement mechanism is not enabled. The number of sensor nodes is fixed to ten. The corrupted packets are dropped without a retransmission. The MAC layer of every node periodically receives a packet from application layer to send with a period of  $T_s$ . The second case is an extension of the first one with application of low-power listening principles and concrete approximation in the carrier sensing operations. To get statistically more reliable results, every simulation is executed 100 times with different seeds for the random number generator, and the metrics are averaged accordingly over all iterations.

The average power consumption of the five operational states is extracted from the datasheet of the transceiver under use. In this work, we use the state-of-the-art commercial wireless sensor node NXP KW41 [10]. The power values are shown in Table 1.

#### Table 1 Average power values for operational states for NXP KW41.

| notation           | power value   |
|--------------------|---------------|
| $P_{ts}$           | 21.8 mW       |
| $P_{rs}$           | 25.3 mW       |
| P <sub>sleep</sub> | 7.2 <i>nW</i> |
| P <sub>ss</sub>    | 24.3 mW       |
| $P_{cs}$           | 24.3 mW       |

#### 4.2 Error Insertion in Packet Transfer

Packet transfer is the most important network operation. During this operation, the actual data is transferred from a source node to a destination node(s) in a transmitter-channel-receiver chain. The circuit level errors in the computational blocks of this chain affects the transformation of the signal and may cause errors during the demodulation and decoding procedures and, hence, the data loss. In fact, the circuit level inaccuracy can be interpreted as a more general form of quantization errors during analog-todigital conversion. The tolerance of those errors can be expressed in the form of Bit-Error-Rate (BER) –  $E_b/N_0$ -relation which is well elaborated in the literature for widely used demodulation and decoding techniques [11].  $E_b$  is an abstract carrier signal energy per bit.  $N_0$  is the inserted noise density. The  $E_b/N_0$  – BER relation for a coherent O-QPSK demodulation was elaborated in python with NumPy package [12]. The result is shown in Fig. 4. The data is produced by insertion of a gaussian equally distributed noise to the O-QPSK modulated signal and attempt to demodulate it using traditional methods.



In contrast to traditional way, we focus on  $N_0/E_b$  instead of  $E_b/N_0$  because  $N_0$  is the parameter of interest.  $N_0$  can be modified to account for approximations in the same way it is conventionally performed for quantization errors. The incoming packet is usually checked for errors after demodulation and decoding, and dropped if the check is failed. In this way, every bit error can cause packet drop. The Packet Error Rate (PER) becomes

$$PER = 1 - (1 - BER)^{N_b/p}.$$
 (8)

 $N_{b/p}$  is the number of bits transferred in a packet. The PER factor can be integrated in the network simulation in postprocessing by reducing the total number of successfully received packets. The corrupt packet will not pass the error check, which however is performed after the signal capturing, demodulation and decoding. Hence for protocols without retransmissions the PER does not affect total energy nor latency. As a consequence, only the goodput and spent energy per bit are affected. The relation from Fig. 4 is used to describe the PER factor during the OMNet++ simulations. As a result,  $N_0/E_b$  can be directly put in relation to the throughput and energy per bit ( $W_b$ ) as shown in Fig. 5.

The network-level calculations are made based on the same power consumption values for accurate and inaccurate circuits. By knowledge of the energy and goodput penalty an inaccurate circuit can be precisely designed with inaccuracy as new precision knob with adequate insight at energy savings. Note that all the plots and estimations in this paper show the penalty caused by circuit-level inaccuracy. The energy benefits of inaccurate computation come from the concrete circuit-level implementation and analysis. Those energy reductions are needed to compensate and overcome the estimated penalty for more energy efficient network operations.

### 4.3 Error Insertion in Preamble Detection

Physical synchronization of nodes is one of the key operations which makes a successful packet transfer possible. One of the synchronization operations is preamble detection. The preamble is extra symbols in front of the actual packet which helps to synchronize the transmitter and receiver. During a preamble detection, the receiver node scans the channel for a packet preamble. If the receiver fails to identify an incoming preamble or falsely identifies the preamble earlier, it will not be able to demodulate or decode the incoming packet. The mechanics are similar to the impact of error on packet transfer, but with an important difference that after an undetected preamble, the node may switch to low power sleep mode to save energy. This can be



Fig. 5 Network penalty from increased noise through circuit level inaccuracy during packet transfer.

done after a predefined timeout  $T_o$ . Depending on the packet synchronization approach, there are two preamble detection error cases: preamble detection error and false preamble detection. However, for approaches with the reception timing estimation, false detection has the same impact as detection error because the expected packet arrives after the false detection and cannot be received. Thus, only the preamble detection error is relevant. In this paper, it is called synchronization error. The network performance penalty for such errors is estimated for some reasonable  $T_o$  values, and synchronization error rates (SER). The results are illustrated in Fig. 6. The goodput decreases linearly with SER while the impact on the spent energy per bit depends on how small the time-out ( $T_o$ ) is.

Another energy efficient synchronization approach is a periodic check of the channel for incoming packets which usually have extra prefix (Low Power Listening [8]). In this case, preamble false detection causes energy penalty for a node to activate the receiver circuits in SS state, listen for non-arriving packet, and go back to energy conserving IS state. The energy penalty can be quantified by

$$W_{b,penalty} = \frac{T_{IS}}{T_{check} \times B_{payload}} \times P_{SS} \times T_o \times FDR_p \tag{9}$$

where  $T_{IS}$  stands for total time of node in idle state,  $T_{check}$  is checking interval in the low power listening technique, and *FDR* is the preamble false detection rate.

#### 4.4 Error Insertion in CCA

One of the network operations which may be affected by the introduction of power saving circuit inaccuracy is the Clear Channel Assessment (CCA), as it is called in IEEE 802.15.4. Two



Fig. 6 Network penalty for detection errors of an incoming preamble.



Fig. 7 Detection error impact on network performance under different sampling rates, latency (a), goodput (b), energy per bit (c).

possible errors caused by approximate CCA circuit (detection error and false detection) can be introduced by randomly flipping the accurate CCA result during the network simulations. False detection and detection error cannot occur simultaneously and have different consequences. Hence, the cases are simulated and investigated separately to isolate and recognize their impact.

The fault insertion is performed during the simulation at the CCA phase. With the probability of CCA Detection Error Rate (DER), the exact CCA estimation is flipped from occupied to a free channel. The resulting behavior is captured in terms of the durations of the MAC phases, successfully received and sent packets. Those values are used to calculate all the introduced power metrics as explained in previous sections. The OMNet++ simulation model code was modified as shown by Eqn (10).

$$CCA_{apx} = \begin{cases} not \ rand_{DER}, & if \ CCA_{exact} = 1\\ rand_{EDR}, & if \ CCA_{exact} = 0 \end{cases}$$
(10)

 $rand_X$  is a binary random generator, which gives 1 with probability X.

The network performance degradation caused by detection errors is illustrated in Fig. 7 for different data generation rates  $T_s$  by the nodes. The results are produced based on a OMNet++ simulations of a non-beacon enabled IEEE 802.15.4 WSN without acknowledgement mechanics. The simulated topology consists of 10 nodes trying to send maximal size packets to a coordinator. For application send requests, the regular sampling model with fixed period  $T_s$  is assumed. It is evident that with increasing  $T_s$ , the circuit inaccuracy impact becomes insignificant. The collisions are less likely with higher  $T_s$ , and the CCA detection error effect on



Fig. 8 False detection impact on performance metrics under different sampling rates, latency (a), goodput (b), energy per bit (c).

goodput and latency decreases. While the goodput is effectively decreased by CCA detection errors, the average transmission delay becomes shorter. The reason for the latency improvement is because the node is less likely to back-off and wait for next opportunity to send. Energy per bit is degrading significantly as illustrated in Fig. 7 c). The total energy decreases for tight  $T_s$  because the nodes spend less time in reception mode. However, the goodput degradation is stronger and the energy per bit as a quotient of total energy and successfully transferred bits is increasing dramatically for very tight  $T_s$  values. Note that this energy difference is the minimum of circuit level energy savings needed on circuit level for a positive energy gain in network level. The tighter is the expected sample period  $T_s$  the more savings are needed at circuit level to compensate the network level fault consequences.

The impact of CCA false detection on CSMA/CA algorithm is that the node sometimes backs-off though the channel is free. The impact of this kind of error is measured by changing the CCA result from free channel to occupied channel with the probability of FDR. The simulation is performed with same parameters as for CCA detection error. The simulation results are illustrated in Fig. 8. In contrast to CCA detection error, false detection leads to considerable effect on latency for relaxed  $T_s$  values because the error probability increases with probability of sensing a free channel. The nodes are more likely to back-off and wait even in presence of a free channel. The throughput is however not affected for sufficiently high maximum back-off numbers. Furthermore, for extremely tight  $T_s$ , the WSN with FDR slightly



Fig. 9 Low power listening principle.

outperforms the accurate network. This is because, in this condition, a false detection prevents natural collisions. For example, two nodes sense a channel simultaneously and they would see a free channel and eventually start a transmission. However, due to a false detection, one node backs-off which effectively prevents the collision. For this simulation, the maximum back-off count parameter (macMaxCSMABackoffs) is set to 4 (default protocol setting). For lower back-off numbers, the impact of CCA false detection on goodput becomes more significant, because the transceiver is more likely to drop the packet because the maximum back off number is reached. Same effect causes the decrease of latency.

#### 4.5 Using the Analysis

The analysis results expose the conditions in which the circuit inaccuracy will bring significant network penalty, and energy efficiency is hard to achieve. Also, the conditions for negligible approximation effect become apparent. As a show case, for network sampling periods higher than  $T_s = 1s$ , inexact CCA approximation is applied. Inspired by additional power improvement through Low Power Listening (LPL) techniques, the same CCA circuit is used as extended preamble detector. The LPL principle is illustrated in Fig. 9. The prefix is an extended preamble which is needed to wake up the receiver node at right time. In this application, the CCA circuit gains in significance for the considered sampling periods. It is because, during the waiting for next reception, the power during CCA operation becomes dominant. Using the analysis of preamble detection errors and CCA detection and false detection errors described in the previous sections, significant energy reductions of up to 20% can be achieved as indicated in Fig. 10. The approximate CCA is designed and analyzed with help of EvoApprox8b adder library [13] and approximate multiplier from [14] with conventional EDA tools [15].

#### Conclusions 5

In this work, circuit-level inaccuracy in transceiver design is categorized and its impact on wireless sensor network performance is analyzed. This is a new angle on RF transceiver design because inaccurate computations were not considered on network level in previous literature. Hence, first the motivation for such an approach is described. Then the most important network performance metrics are defined, and a wireless sensor node model is described which is used for modeling of the circuitlevel inaccuracy. The main contribution of the paper is a general analysis approach, which elaborates the impact of circuit-level



Fig. 10 Average power savings in a network using LPL and an inaccurate CCA circuit.

inaccuracy on network-level performance. For demonstration, the investigation is applied in detail on several non-beacon enabled IEEE 802.15.4 cases. This analysis shows that the effect of the circuit-level inaccuracy on the network performance is not straightforward. It shows the network penalty for errors in circuit-level computations at different network configurations, giving insight whether the inaccuracies are controllable. The results show that it is possible to exploit circuit-level inaccuracy to provide further energy gain in wireless sensor networks enabling new application possibilities.

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