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Comparing the Energy Efficiency of Communication Protocols based on Constructive Interference

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***Abstract*—The use of energy-efficient wireless communication protocols is a prerequisite for long lifetimes of wireless sensor networks (*WSN*s). While conventional communication protocols target to minimize concurrent transmissions to avoid collisions, a new paradigm that exploits the opposite case has been proposed in [1]. Relying on the physical effect of *constructive interference*, transmissions are being sent by multiple nodes in a tightly time-synchronized fashion in order to increase transmission range and signal quality. The high reliability and fast data dissemination of this approach has led to numerous new protocols being presented in the last years. However, a comparative evaluation of the energy efficiency of these protocols has not been published to date. In this paper, we hence present an energy consumption assessment of two communication protocols which exploit constructive interference. We measure the power consumption of actual node hardware in practical experiments, such that a high degree of realism is given. Moreover, we investigate several combinations of transmission power settings and packet sizes in order to determine how communication protocol parameters affect the energy consumption values. Our results show that large discrepancies in energy consumption exist for two protocols based one the same principle.**

I. Introduction

Wireless sensor nodes are anticipated to find widespread use in numerous application scenarios, e.g., precision agriculture, logistics, biomedical sensing, or the realization of smart cities. This expected growth of wireless sensing technologies will lead to a tremendous volume of data that has to be gathered in an accurate and efficient way. In order to establish the technological foundation for such large-scale sensor networks, an adequate selection of the underlying communication protocol is of paramount importance. As most sensors are expected to be powered by batteries, a commonality of all candidate protocols is the need to operate with minimal energy consumption. Besides identifying and implementing communication protocols, it is thus also particularly important to assess their performance and energy efficiency.

Several papers have been published on communication protocols that exploit constructive interference (CI) in recent years, including the works introducing Glossy [1], P3 [2], Chaos [3], RFT [4], and others [5–8]. Nonetheless, it proves to be challenging to select the most appropriate protocol that satisfies the requirements for a specific application scenario. The reason is that many CI-based protocols lack comparative evaluations against other CI-based protocols. Available approaches in low-power wireless networkings rarely provide information on how much energy is used by a communication protocol or how the energy demand of a protocol changes when the default configuration (packet sizes, transmission power settings, etc) is modified. Instead, the most widely adopted solution to demonstrate a protocol's energy efficiency is to present their radio duty cycle, i.e., during what fraction of time the radio has been turned on. The aim of this paper does not lie in introducing a new communication protocol but rather to *compare the energy consumption* of existing protocols. To our best knowledge, this is the first paper to present such an energy analysis for this type of communication protocols.

This paper is structured as follows. First, we present details on the concept of constructive interference and the evaluated protocols relying on it in Sec. II. Subsequently, we describe our evaluation settings in Sec. III, before discussing the obtained results when varying the protocol settings in Sec. IV. At last, we conclude the paper in Sec. V.

II. Communication Protocol Selection

In our comparative energy assessment study, we focus on communication protocols that exploit constructive interference because they provide fast packet propagation and a high reliability of successful data transmissions. In fact, such communication protocols are able to disseminate a message to the network within milliseconds and, depending on the transmission power setting and the network size, up to 99.99% packet reception can be reached [1]. In order to lay the foundation for the remainder of this paper, the concept of CI is revisited briefly before introducing the chosen communication protocols in more detail.

A. Constructive Interference

The physical phenomenon of CI occurs when two or more wireless transmitters send the same data simultaneously into the same medium. A visualization of the phenomenon is given in Fig. 1, where we assume that two stations simultaneously send the same message. Consequently, their signals exhibit the same waveforms and are transmitted at the same time (i.e., there is no phase shift between them).

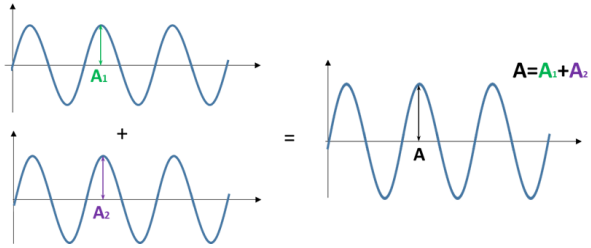

Fig. 1. Visualization of the concept of Constructive Interference

By applying wave superposition, the resulting waveform on the medium can be computed as the sum of all contributing waves' amplitudes. For the example in the figure, the resulting signal thus features the same waveform as the two input signals, yet with a larger amplitude. Several studies on CI have been conducted in the past years, and it has been found that the "collision" between synchronized signals that share the same characteristics most often leads to constructive interference instead of mutual signal destruction. The application of CI thus has a benefit on message broadcasting, because it allows for increasing the transmission range without having to rely on higher transmission power settings. Hence, its application effectively requires less hops than necessary for traditional protocols in order to cover the same geographic distance [1].

In this study, we compare two existing communication protocols that use CI regarding their energy consumption. More specifically, we have chosen Glossy [1] and Chaos [3] because at the time of conducting this research, those were the only two protocols with openly published source codes. Furthermore, Glossy was the first communication protocol able to transmit messages using CI and is also the basis for all the other communication protocols that rely on wave interference.

B. Glossy

The main concept behind Glossy is to disseminate the same message to all devices in a WSN. Glossy employs three main techniques:

1) Concurrent transmissions: In order to maximize the effect of CI, almost all message transmissions are triggered by the reception of a packet from another device. Only the very first message transmission has to be started by a single *initiator* node. This way, the network achieves a tight synchronization of its nodes, which in turn enables the possibility to exploit constructive interference and minimizes the chances of destructive packet corruption.

2) Time synchronization: This feature is reached due to the usage of a special design of all propagated messages. On the one hand, each message has a one byte counter field which is incremented by every node that forwards the message. On the other hand, the initiator of the flood adds its local time (i.e., the value of its clock at the time of transmission) to the broadcasted message. Because the content of the propagated message is not modified, each receiving node can locally calculate when the flood has started using the values of the embedded counter and the initiator clock value. This way, all nodes fulfill the requirement of close synchronization.

3) Temporal decoupling: Because the communication protocol pre-defines the intervals at which messages can be flooded into the network, Glossy is able to effectively prevent collisions between its own messages, and can even mitigate the negative impact of other applications running in parallel.

C. Chaos

Even though Chaos [3] is also based on CI, it differs from Glossy in several regards. First and foremost, Chaos is an all-to-all transmission scheme with support for in-network processing while Glossy targets the transmission of a message between one sender and all receivers. Glossy merely floods the message to the entire network in order to increase the chance of successful delivery to the receiver. In Chaos, every node can send messages different from the ones transmitted by its neighbors. Therefore, the full potential of CI is only exploited when neighboring nodes send identical packets. However, even when different messages are being sent simultaneously, another phenomenon comes to the rescue, called the *capture effect* [9]. It ensures that when several different messages are being sent simultaneously, a receiving node will only decode the strongest signal and disregard the others.

To achieve an all-to-all scheme, Chaos employs parallel collection, processing, and dissemination within the network through two mechanisms: synchronized transmission and programmable merge operator. The former technique, synchronous transmission, is exploited when nodes have new data they wish to transmit. Each device with data to share sends their messages at the same time, however the different contents will not lead to CI, but result in the capture effect instead. After reception, nodes merge their local data with the content of the received packet and re-transmit the packet in a synchronous fashion. The process of merging data is made with the help of the merge operator that is defined by the user that is implementing Chaos. The core principles of Chaos are:

1) Communication and Processing Support: This communication protocol relies on the notion of *data processing* because each time a packet is received, the receiving node has to modify the flags in its header and the values in its payload according to the used merge operator. To ensure synchronous transmission with a merge operator on each node, the duration of the task has to last the same time for all the nodes. To solve this matter, developers must decide on a fixed period of time for the processing and transmission task, avoiding time displacement.

2) Transmission balance: Chaos predominantly uses the capture effect for message propagation, while CI is only used when nodes have no more additional information to add. However, researchers have demonstrated the scalability limitations of the capture effect [10] in dense networks. Hence, means to exchange control messages have been included through the a field of flags contained in exchanged packets. These flags are used to let nodes decide (i) whether to transmit or not, (ii) when to re-initiate communication because of a possible premature halt, or (iii) to share the final result aggressively in order to reduce energy costs.

D. Analytical Comparison

Before carrying out our practical measurements in Sec. III, we first formulate our expectations to the energy demand based on the values reported in the papers introducing Glossy [1] and Chaos [3]. In both publications, the *radio on-time* (i.e., the amount of time per message transmission during which the radio transceiver is not powered down) has been used as a metric for the expected energy consumption of the devices in the WSN rather than performing actual consumption measurements using hardware instrumentation. As both protocols have been evaluated on the TelosB platform [11], reported results for radio-on times can be expected to be comparable.

The authors have documented the following results from their experimental evaluations of the two protocols. The radio on-time of Glossy has been stated to depend on the number of retransmissions of each packet. Radio on-times in the experiments conducted in [1] (using between 1 and 6 transmissions per node) for a payload size of 8 bytes have been shown to range between 2 ms and 11 ms. The values determined for radio on-times in Chaos in [3] are commonly at least 10 times larger, ranging between 100 ms and approximately 400 ms. Most likely this can be attributed to (a) the slightly larger payload size of 10 bytes, (b) the data processing time of 2,000 clock cycles (during which the transceiver stays active), and (c) the fact the the processing support initially leads to a prevalence of the capture effect before the benefits of constructive interference become apparent. We thus expect to observe a similar ratio for the results of our evaluation.

III. Evaluation Setup

Based on the reasons stated in the previous section we will confine our analysis to Glossy and Chaos. Despite our desire to assess the energy demand of other protocols, the unavailability of their software implementations for the MSP430 microcontroller and CC2420 radio (present on the TelosB platform [11]) has hampered us in this regard. The four evaluations are based on a WSN deployment based on TelosB devices, one of which has been connected to a Hitex PowerScale power analyzer [12]. The reason to use the PowerScale for our measurements is its high sampling rate (up to 100 kHz) and its fine amplitude resolution (supporting currents between 200 nA and 500 mA). Thus, this setup allows us to better capture and understand the power difference between two communication protocols.

The evaluation of both protocols is conducted in the same environmental conditions and consists of measuring the energy consumption requirements when one node is sending data to the rest of the nodes. Our motivation to measure the energy demand of a receiver node (and not the initiator) is based on the fact that the network is predominantly constituted of receivers while there is only a single initiator for each flood. As such, the receivers' energy consumption can be expected to reflect the average consumption of the network better. Moreover, the initiator needs to keep its radio transceiver activated for the entire duration of a flood, and thus generally exhibits a higher energy demand than the receiving nodes.

A. Conducted experiments

Power consumption measurements for the two CI-based communication protocols were conducted during their *data transmission* periods, and any protocol-specific coordination overhead has been disregarded. With that being said, we can limit our parameter variations to changes of the payload size of sent messages as well as the used transmission power settings of the radio. Both settings can be easily adapted in either communication protocol through changes to their software implementations.

In Chaos, due to the special header that each packet must have, the useable range of payload sizes can vary between 1 and 100 bytes. For this reason, the evaluations were conducted with payload sizes of 10 and 100 bytes, respectively. This way, we cater to a fair comparison of both protocols in the extremal cases of quite small and very large packets. The CC2420 radio on the TelosB platform supports eight different transmission power settings parameters, ranging from -25 dBm to 0 dBm. Thus, we assess the energy demand of each analyzed CI-based communication protocol for the following four configurations:

1) -25 dBm transmission power / 10 bytes payload size
2) 0 dBm transmission power / 100 bytes payload size
3) -25 dBm transmission power / 100 bytes payload size
4) 0 dBm transmission power / 10 bytes payload size

IV. Results and Discussion

We have conducted five repetitions for each of the evaluation configurations described in Sec. III, and report the mean power consumption for each of our energy assessments as follows.

A. Glossy

Energy consumption results for the Glossy protocol are shown in Fig. 2. The y-axis depicts the required average power in each experiment in milliwatts, whereas the four experimental configurations are shown as individual bars along the x-axis. The figure shows that using different transmission power settings while maintaining the same packet size leads to small, but measurable changes in the node's power demand. For the packets of 10 bytes size, a difference of 8.16% can be observed, increasing to an 15.25% for the payload size of 100 bytes. These results can be attributed to the characteristics

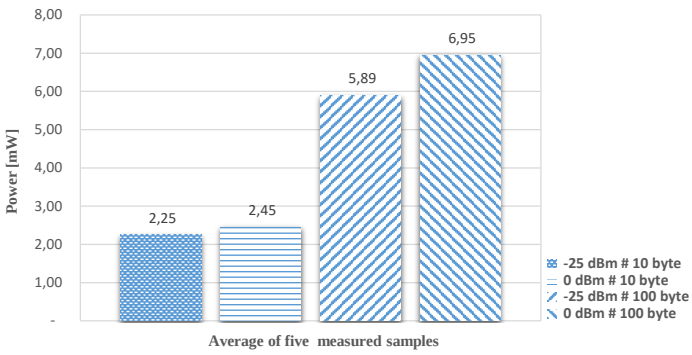

Fig. 2. Average platform power demand when running Glossy

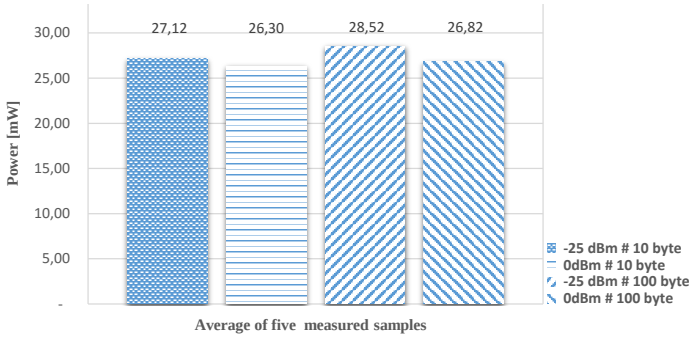

Fig. 3. Average platform power demand when running Chaos

of the CC2420 radio transceiver, whose power consumption is not proportional to the transmission power setting. At the same time, the results indicate that running Glossy with reduced transmission power (and thus strongly reducing wireless range) only leads to comparably small savings, especially as more nodes are required in such cases to ensure the network's connectivity. When keeping the same transmission power level and varying the size of the transmitted payloads, a larger difference in the power demand can be observed. For the $-25\,\mathrm{dBm}$ transmission power setting, the tenfold increase in packet size leads to a power consumption increase by 261%. For the $0\,\mathrm{dBm}$ setting, the increase is even more notable at 284%. In both cases, the primary cause for the increased demand is the need to keep the radio active for longer periods.

B. Chaos

Similar to the results presented in the previous section, a dependency can be observed between transmission power and payload size for Chaos, as shown in Fig. 3. For samples with identical payload size but different transmission power levels, we even observe minor decreases in power consumption of 3.02% (10 bytes) and 5.96% (100 bytes). For the same transmission power but with different payload sizes, the results show a difference of 4.91% (-25dBm) and 1.93% (0dBm) in power consumption, respectively. This can be most likely attributed to the increased number of retransmissions in order to fully transfer all data, impacted by the small transmission radius in the $-25\,\mathrm{dBm}$ setting. This incoherence is given by the fact that Chaos majorly takes advantage of capture effect; and therefore, if payloads are transmitted at a low transmission power, they do not arrive to the receiver with enough accuracy and will be discarded by the receiver. Another observation is that packet size differences have a very small impact on the total energy demand, while generally power consumption levels are up to four times higher than for Glossy. This higher continuous power demand is likely to be a result of the default Chaos configuration, which have not changed apart from modifying payload sizes and transmission power levels.

It needs to be added at this point that the experimentally determined power consumptions of Glossy and Chaos meet our expectations formulated in Sec. II-D. Across our measurements, Chaos still needs between 4 and 12 times more electrical power for its operation.

V. Conclusions

The aim of this paper was to obtain energy measurements through a series of assessments for a better understanding of communication protocols that exploit constructive interference. We have thus derived a measurement setup and adapted implementations of both protocols in order to determine the impact of payload size and transmission power on a node's overall energy consumption. Our results demonstrate that the sole consideration of radio duty cycles in simulation environments does not appear to fully reflect the power consumption, because real-world effects are not captured in such settings. We thus strongly argue in favor of conducting real-world experiments to validate simulative findings. In the future, we want to compare more implementations of communication protocols using CI in order to get a deeper understanding of factors contributing the a protocol's energy demand.

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