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Green partial packet recovery in wireless sensor networks ☆

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ABSTRACT

Partial packet recovery is well known for increasing network throughput and reducing frame retransmissions. However, partial packet recovery methods in the literature are not energy-aware and hence they are not suitable for the battery powered wireless sensor motes. We propose Green-Frag, a novel adaptive partial packet recovery mechanism that is energy friendly. It can help prolonging the battery life of wireless sensor motes that are usually resource constrained. It dynamically partitions the frame into smaller blocks to avoid dropping the whole frame due to a single bit error. Also, Green-Frag is able to tolerate high interference and save energy by varying the transmit power based on channel quality and interference pattern. We experimentally evaluate the energy efficiency as well as goodput and delay of Green-Frag using our TelosB sensor mote testbed. We find that Green-Frag reduces energy consumption by 33% on average compared to the state of the art partial packet recovery scheme in the literature in the presence of Wi-Fi interference. In the worst case, this reduction in energy consumption comes at the cost of 10% reduction in goodput. Finally, Green-Frag reduces the latency by 22% on average compared to other static frame fragmentation schemes.

1. Introduction

Power management is an active area of research in Wireless Sensor Networks (WSNs). Efficient power management in WSN is necessary because wireless motes are usually battery-powered and are often deployed in mission-critical applications. For WSN motes to be energy efficient, they should be able to smartly choose both frame size and transmit power based on channel interference level. In fact, finding the optimal frame size is challenging in wireless networks. Large frames can provide good channel bandwidth utilization due to its low overhead in low interference environments. On the other hand, when the channel quality is bad, small frames provide better network utilization because of less overhead in the error recovery process. Large frames are often used in wired communication because the wired channel has low bit-error rate (BER), typically 10^{-15}–10^{-12}. However, the BER in wireless networks is orders of magnitude higher (Jamshaid, 2010), typically 10^{-5}–10^{-3}. Additionally, BER in wireless networks changes dramatically over short time intervals (Ganti et al., 2006; Miu et al., 2005; Dubois-Ferrière et al., 2005; Aguayo et al., 2004; Jardosh et al., 2005). In fact, partial packet recovery techniques may be used to solve this issue retransmitting only the corrupted portion of the previously transmitted frame. However, current partial packet recovery mechanisms have only focused on improving the throughput by limiting retransmissions (Luo et al., 2012). The energy efficiency aspect of these schemes has never been studied in the literature.

In general, WSN protocols use small data frames to avoid the overhead associated with retransmitting lost or corrupted frames. However, these small frames incur high overhead as each of these frames need additional PHY and MAC layer headers. These headers include sender and receiver IDs, CRC for error detection, and additional bytes for synchronization. The data link layer is responsible for partitioning the original payload into frames. Thus, when the wireless channel BER is low, using large frames help amortizing the PHY and MAC header overhead over large data payloads. Once BER becomes high, large frames could effectively lower the overall throughput due to more frequent retransmissions of large frames. Thus, the optimal frame size depends on the wireless channel quality, which varies over time and environmental conditions (Modiano, 1999; Dong et al., 2010). Previously, we proposed two dynamic frame fragmentation schemes for WSNs, iFrag (Showail et al., 2014) and Hi-Frag (Meer et al., 2015). These aim to achieve high goodput by dynamically changing frame partitioning according to the channel conditions.

☆ A preliminary versions of this work (Daghistani and Shihada, 2013) was presented at IEEE WiMob2013 and received the best student paper award.

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In this paper, we analyze recent frame fragmentation schemes from both energy efficiency and throughput perspective. We experimentally compare two main types of frame fragmentation techniques, static and dynamic, in order to find the most energy-efficient scheme. We show that dynamic frame fragmentation techniques outperform other static approaches in terms of energy efficiency. Hence, using the most energy-efficient dynamic frame fragmentation scheme we develop a green protocol that can adapt to interference patterns. This novel scheme is called Green-Frag and it considers the environmental interference levels and patterns when deciding about the optimal frame structure and transmit power. Green-Frag aims to achieve high level of energy efficiency in all channel situations while maintaining a good level of throughput and delay performance.

Our experimental analysis shows that Green-Frag outperforms all other schemes in terms of energy-efficiency while maintaining comparable throughput and delay.

The main contributions of this paper are as follows:

(1) Compare existing frame fragmentation schemes proposed in the literature for WSNs in terms of energy consumption.
(2) Design, implement, and evaluate a green partial packet recovery scheme for WSN motes that adapts the motes transmit power based on channel quality.
(3) Propose a novel method for experimentally calculating the energy consumption in WSN motes.

This paper is organized as follows. Section 2 provides an executive summary of existing partial packet recovery protocols. Section 3 provides an energy evaluation of various static and dynamic frame fragmentation schemes, which also serves as a motivation for Green-Frag. In Section 4, we introduce Green-Frag and various considerations governing its design. Section 5 presents our experimental results. Finally, the conclusion and future work is discussed in Section 6.

2. Related work

There is a lack of literature on energy efficient partial packet recovery techniques. In fact, the main focus of all of the proposed partial packet recovery techniques is on increasing the throughput without studying the effects of these techniques on energy consumption. To the best of our knowledge, this work is the first experimental analysis that studies various partial packet recovery techniques from an energy consumption perspective. In this section, we discuss previous partial packet recovery techniques that were proposed in the literature.

Frame fragmentation is one of the partial packet recovery approaches. Frame fragmentation techniques can be classified into two categories: static or dynamic, based on whether they use fixed or dynamic frame sizes. One of the main static frame fragmentation techniques is Seda (Ganti et al., 2006). Seda main target is to enhance WSN throughput by reducing the number of retransmissions. Its design includes a number of enhancements that can improve the network throughput, such as reduced retransmissions and the use of compact acknowledgment (ACK) frame. Seda divides each frame into identical-sized blocks. It then adds a block number and a Cyclic Redundancy Check (CRC) to each block. This allows the receiver to identify corrupted blocks and only request for their retransmission. The authors of Seda claim that a block size of 20–25 bytes provides near-optimal throughput. However, this is not always correct because it highly depends on both the channel condition and the Bit Error Ratio (BER) as we show in Showail et al. (2014). A similar static partial packet recovery technique, but for wireless local area networks, was proposed in Kuo et al. (2007). This scheme is called Fragment-Based Retransmission (FBR) and it works as follows. Within the same channel access, the sender tries to retransmit all the corrupted blocks. In fact, the authors mentioned that either 2 or 4 blocks could be used per packet. However, they did not discuss on what basis FBR is going to choose the number of blocks per frame. Moreover, it is not clear how the receiver is going to figure out the number of sent blocks per frame given that it changes over time. Finally, network fairness could be significantly degraded due to the extension of the sender transmission chance.

There are other partial packet recovery techniques in the literature that are dynamically changing the size of packet blocks. Zhou and Wang (2006) try to maximize the throughput by proposing an adaptive subpacket scheme that optimizes the block size. The adaptive algorithm depends on SNR of the channel to change blocks' sizes. However, the authors never mentioned how does the receiver know once the sender decides to change the size of the blocks. Moreover, it is not possible to preserve data integrity without having a block number assigned to each block. In Willig (2009), the author proposed to use Luby-type erasure code for symbol recovery. The protocol depends on the channel BER to select the segment size. However, the author assumed that the sender has a precise knowledge of the channel BER, which is not realistic. Moreover, the assumption that the feedback channel is error-free and has no delay is not always true. In a similar work, Zhu (2012) proposed an adaptive frame fragmentation scheme for Wireless Local Area Networks (WLANs) called Gathering Error-free Blocks (GEB). The main idea behind GEB is simple, the sender divides the frame into several blocks and the receiver gathers the error-free ones in order to assemble the original frame. GEB differentiates between dropped frames due to collision or due to high interference and adjust the contention window accordingly. This scheme suffers from unnecessary overhead because the error detection code is duplicated in the frame level as well as in the block level.

iFrag (Showail et al., 2014) and Hi-Frag (Meer et al., 2015) are two recent dynamic frame fragmentation schemes that were specifically designed to suite WSNs. iFrag (Showail et al., 2014) is a dynamic block size allocation protocol that adapts the block size based on current channel conditions, leading to lower block loss rates and a significant reduction in block retransmissions. This improves data transmission reliability, resulting in high network throughput. iFrag changes the partitioning size of frames dynamically depending on transmission history and some predefined thresholds. It has four predefined data frame modes, each of them partitioned differently. The four data frame mode structures are named `iFrag 1`, `iFrag 2`, `iFrag 4`, and `iFrag 8` where the numbers represent the number of data blocks in the frame structure. As the number of blocks in the frame increases, the frame size increases since every block needs to have its own block number and error detection code. Hence, modes with smaller block sizes have higher overhead. The other scheme is called hybrid interference-resilient frame fragmentation (Hi-Frag) (Meer et al., 2015). Hi-Frag is designed to reduce unnecessary retransmissions and lower the loss rates, leading to higher throughput. It does that by adaptively changing block sizes and arrangements within data frames according to the interference level and patterns. Unlike iFrag (Showail et al., 2014), it dynamically divides frames to blocks according to the observed error patterns. Also, Hi -Frag frames can contain heterogeneous blocks, i.e. blocks with different sizes within a single data frame. Moreover, Hi-Frag reduces the per block overhead by introducing a new way of identifying block sequence numbers without necessarily having a specific field for that. This reduces the fragmentation process overhead by 50% compared to iFrag and Seda.

Another approach for recovering the part of the packet that is corrupted is packet combining. Dubois-Ferrière et al. (2005) recovers bit errors by combining packets on the frame level. However, it is different from other frame fragmentation schemes