Use of Framelets for Efficient Transmitter-Receiver Rendezvous in Wireless Sensor Networks

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Abstract

A basic problem introduced by the use of radio duty cycles as an energy saving technique is the need to establish rendezvous between transmitter and receiver. Since communication can only take place when the receiver's radio is active, the transmission of frames needs to somehow overlap with this active period.

This paper investigates the use of framelets - small, fixed sized frames - to achieve transmitter-receiver rendezvous and contrasts this technique with the use of long frames. The benefits of applying framelets is assessed analytically and an implementation of the concept for the DSYS25 sensor platform is presented and evaluated. The results show that substantial energy savings can be achieved with framelets as well as an increase in communication throughput.

1. Introduction and Motivation

Wireless sensor networks are a collection of autonomous devices with computational, sensing and wireless communication capabilities. A major constraint in the design of these systems is the need of autonomous, untethered operation for extended periods of time. The system lifetime is ultimately defined by the energy-efficiency of the design which is specially affected by the way the communication system is operated.

Generally, a sensor transceiver can be set to one of four states: *transmitting*, *receiving*, *listening* or *sleeping*. Energy efficient operation of transceivers is achieved essentially by keeping them in sleeping mode as often as possible. The sleeping state generally consumes orders of magnitude less energy than the active states (transmitting/receiving/listening). However, as communication cannot take place between nodes while the transceivers are in sleeping state, sender and receiver actions must be synchronized for transmission.

Currently different strategies can be used to provide transmitter-receiver synchronization such as the use of *wake-up radios*, *shared time basis*, *application layer knowledge* or *duty cycles*. The common element of all these techniques is the need to establish, in an efficient way, an intersection of data transmission and listening activities enabling effective communication between transceiver and receiver. Such an intersection is called *transmitter-receiver rendezvous* and can be achieved at different costs by each technique or a combination of them.

Given its generality and simplicity, this paper focuses on transmitter-receiver rendezvous in relation to transceivers operating with a duty cycle. In particular, this paper presents a detailed assessment of the use of framelets - small, fixed-sized frames - to achieve rendezvous and contrasts this technique with the well-established technique of long frames. The benefits of applying framelets is assessed analytically and an implementation of this concept for the DSYS25 sensor platform [3] is presented and evaluated. The results show that substantial energy savings can be achieved and the communication throughput can be increased if framelets are used.

The rest of the paper is organized as follows. Section 2 describes the different methods for rendezvous in duty-cycled systems. Section 3 presents the framelet approach and describes framelet techniques that impact the performance of the communication stack. Section 4 analyzes the framelet approach in terms of energy efficiency and throughput. Section 5 overviews the implementation of the framelet approach for the DSYS25 sensor platform. Section 6 presents experimental results obtained by using the DSYS25 platform and compares the results with the analytical evaluation. Section 7 describes and comments on related work. The paper ends with conclusions and ideas for future work.

2. Transmitter-Receiver Rendezvous with Duty Cycles

A basic problem introduced by the use of radio duty cycles as an energy saving technique is the need to establish rendezvous between transmitter and receiver. Since communication can only take place when the receiver's radio is active, the transmission of frames needs to somehow overlap with this active period. *Transmitter-receiver rendezvous* is the overlapping of data transmission and listening activities enabling effective communication.

To implement the duty cycle approach, no time synchronization between communicating nodes is necessary. However, this can only be achieved at the expense of extra overhead per frame communicated. In the following paragraphs, two possible approaches to implement rendezvous in duty-cycled systems are given. These two approaches mainly differ in the way data frames are constructed and used, thus incurring different communication overhead.

2.1. Assumptions and Definitions

It is assumed that the clock of transmitter/receiver operates at approximately the same rate. It is also assumed that a fixed rate radio duty cycle is used, i.e., each node periodically activates its radio for a fixed time interval to monitor activity in the channel. The *duty cycle period* is represented as $P = \Delta + \Delta_0$, where Δ is the time the radio remains active and Δ_0 is the time the radio rests in sleeping mode. The *duty cycle ratio*, or duty cycle for short, is defined as:

$$Duty\ Cycle = \frac{\Delta}{P} = \frac{\Delta}{\Delta + \Delta_0}$$

2.2. Rendezvous using Long Frames

A common approach to establish asynchronous rendezvous between transmitter and receiver is the use of long frames. In particular, the frame adopts a long preamble to ensure an overlap between transmission and listening activities. If the receiver captures a portion of the preamble, it keeps the radio active until the entire payload is received. This mechanism was adopted in B-MAC [8]. In order to guarantee rendezvous, the frame must be larger than Δ_0(see Fig. 1).

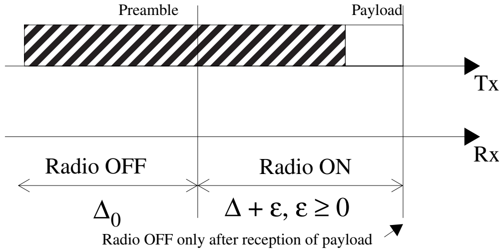

Figure 1. Transmitter-receiver rendezvous using long frames

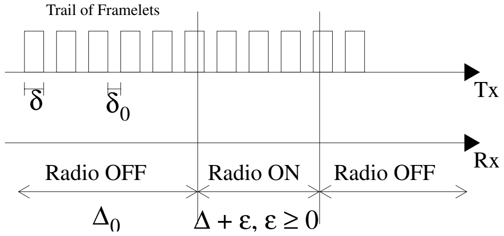

Figure 2. Transmitter-receiver rendezvous using framelets

2.3. Rendezvous using Framelets

Framelets are small, fixed-sized frames that can be transmitted at high speeds. Certain types of ultra low-power transceivers, such as the Nordic nRF2401 [1], are able to transmit small frames at speeds of typically 1Mb/s. A sensor network frame of 32 bytes can therefore be transmitted in 1/4 of a millisecond. Framelets are defined as having a fixed-size. Therefore it is not possible to achieve transmitter-receiver rendezvous through the extension of frame preambles. Instead, rendezvous requires the repeated transmission of several frames containing the entire payload as depicted in Fig. 2. If the receiver captures one framelet, the payload is received. The trail of framelets is defined by three parameters:

- *Number of transmissions*: n
- *Time between framelets*: δ_0
- *Framelet transmission time*: δ

In order to ensure rendezvous, a proper relation between these parameters and Δ, Δ_0 must be obeyed. First, the active portion of duty cycle must be such that:

$$\Delta \geq 2 \cdot \delta + \delta_0 \qquad (1)$$

Furthermore, to ensure overlap between transmission and listening activities, the number of retransmissions n needs to comply with the following inequality when $\Delta_0 > 0$:

$$n \geq \left\lceil \frac{\Delta_0 + 2 \cdot \delta + \delta_0}{\delta + \delta_0} \right\rceil \tag{2}$$

In general, the values of δ and δ_0 should be as small as possible, as this influences according to 1 the minimal possible active time Δ of the duty cycle. The duration of the time Δ determines message delay, throughput and energy savings as shown in the next section.

3. The Framelet Approach

Framelets achieve transmitter-receiver rendezvous and also contain the data that has to be sent. A transmitter includes a payload replica in every framelet transmitted. If all the data to be sent fits in one framelet, then the receiver is spared from extending its active portion of the duty cycle to capture data, as often occurs in the rendezvous technique with long frames. Data replica framelets can be applied even when fragmentation is necessary, as explained later in this section.

The framelet approach offers a few techniques that impact the performance of the communication stack in terms of energy efficiency, transmission latency and throughput. The following paragraphs describe these techniques.

3.1. Acknowledgment

Framelets can be individually acknowledged by the receiver. Combined with the use of data replica framelets, this technique allows the transmitter to stop resending framelets shortly after rendezvous is established. If acknowledgments are not used, or are used only after the successful delivery of the last frame, the transmitter is forced to resend no less than the number of frames specified in inequality 2.

3.2. Interleaving

A singularity of establishing rendezvous through framelets is the possibility of interleaved reception of frames as depicted in Fig. 3. Several transmitters can send a message to a receiver over the shared media at the same time. Normally this would result in a collision of both transmissions with the result of losing both. If interleaving is used, there is a greater likelihood that one framelet of each transmission is received correctly by the destination node. Thus, interleaving has the potential of increasing the channel throughput.

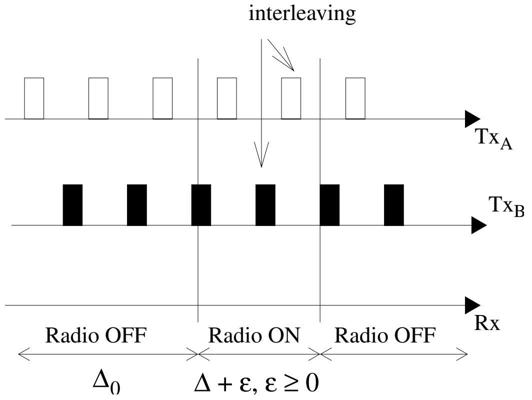

Figure 3. Interleaved reception of framelets

3.3. Fragmentation

Although many applications of wireless sensor networks are expected to require very small frames, some deployments will involve larger payloads. If the physical layer of the sensor node only supports framelets, a fragmentation layer becomes necessary. The first fragment may be transmitted multiple times to guarantee rendezvous with the receiver. After rendezvous is established and the first fragment is acknowledged, each remainder fragment can be subsequently transmitted. It is assumed that the first framelet indicates of how many framelets the whole message consists. This allows the receiver to determine how long the radio must be kept turned on.

4. Analytical Evaluation

This section compares analytically the transceiver energy consumption of the *framelet* and the *long preamble* approach. Here the impact of acknowledgments is examined. Additionally, the impact of interleaving on the channel throughput is assessed.

4.1. Energy Savings

The presentation of the previous techniques suggests that a rendezvous approach combining data replica framelets and acknowledgments offers important energy saving opportunities over a rendezvous approach with long frames. Fig. 4 exemplifies such opportunities. A sender starts the transmission of the framelets and after receiving the acknowledgment from a receiver the transmission can be terminated. Without the acknowledgment the transmission would have to be continued until all framelets are transmitted. Obviously the ac-

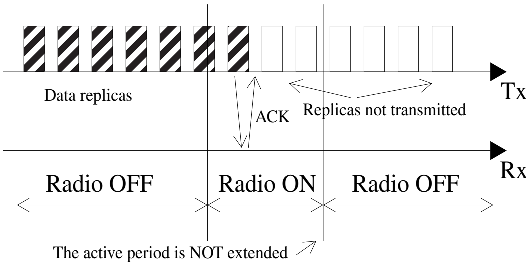

Figure 4. Energy saving opportunities of a framelet rendezvous approach with acknowledgments

knowledgments help to reduce the number of energy costly framelet transmissions.

The following metrics are used to compare a rendezvous approach using long frames with one using framelets and acknowledgments:

- *Transmitter sending time* (τ): defined as the difference between the instant T_b a transmitter begins sending a message and the instant T_e transmission stops.
- *Radio activation time at receiver* (ρ): time the receiver maintains its radio active from its last activation to the end of message reception.

The lower the expected values of τ and ρ, the more energy efficient is the rendezvous technique.

It is assumed that a transmitter generates messages according to a Poisson distribution at a rate of λ messages per unit of time. Each message fits entirely in a framelet and the traffic generated does not overload the capacity of the channel. A receiver operates at fixed duty cycle of period $P = \Delta + \Delta_0$ collecting the transmitted data. The time frame for the analysis is such that $t = 0$ coincides with the beginning of the active portion of the duty cycle at the receiver. Both rendezvous approaches (framelet and long frame) are assumed to require the same values of Δ and Δ_0.

Transmitter sending time (τ). When communication takes place using the framelet rendezvous approach, the transmitter sending time τ is a function of the sending instant T_b, which is a random variable exponentially distributed with parameter λ. In particular, τ is defined as follows:

$$\tau(T_b = t) \leq \begin{cases} \delta & 0 \leq t \leq \Delta - \delta \\ P + \delta + \delta_0 - t & \Delta - \delta \leq t \leq P \\ \tau(t - k \cdot P) & k = \left| \frac{t}{P} \right|, t > P \end{cases} \qquad (3)$$

If the probability distribution function of T_b is represented as $f(T_b = t)$, then the expected value of τ is:

$$E_{framelet}(\tau) \leq \int_{-\infty}^{\infty} \tau(t) \cdot f(t) \cdot dt \qquad (4)$$

or

$$E_{framelet}(\tau) \leq$$

$$\frac{e^{-\lambda(\Delta-\delta)}(\Delta_0 + \delta_0 + \delta - \frac{1}{\lambda}) + e^{-\lambda P}(\frac{1}{\lambda} - \delta - \delta_0) + \delta}{1 - e^{-\lambda P}}$$

On the other hand, when communication takes place using the long frame rendezvous approach, the transmitter sending time τ is fixed and must be such that:

$$E_{long}(\tau) \geq \Delta_0 + \delta \qquad (5)$$

where δ is the time to transmit the payload. Therefore, the reduction of transmitter sending time can be expressed as:

$$Reduction_{\tau} = 1 - \frac{E_{framelet}(\tau)}{E_{long}(\tau)} \qquad (6)$$

Fig. 5 plots $Reduction_{\tau}$ as a function of the radio duty cycle for normal parameters used in the implementation of the framelets approach for the DSYS25 sensor platform (δ=1ms, δ_0=9ms, Δ=15ms). The message arrival rate is one message per nine radio duty cycles (δ=1/9P).

Radio activation time at receiver(ρ). When communication takes place using the framelet rendezvous approach, the radio activation time at the receiver ρ is fixed and equal to Δ. Therefore, the expected value of ρ is:

$$E_{framelet}(\rho) = \Delta \qquad (7)$$

On the other hand, when communication takes place using the long frame rendezvous approach, the radio activation time at the receiver ρ is a function of instant T_e, which is a random variable exponentially distributed with parameter λ. In particular, is defined as follows:

$$\rho(T_e = t) \geq \begin{cases} P & 0 \leq t < \delta \\ \Delta & \delta \leq t \leq \Delta \\ t & \Delta < t \leq P \\ \rho(t - k \cdot P) & k = \left\lfloor \frac{t}{P} \right\rfloor, t > P \end{cases} \qquad (8)$$

The expected value for ρ is calculated similarly to expression 4 and results in:

$$E_{framelet}(\rho) \geq \frac{\frac{e^{-\lambda\Delta}}{\lambda} - \Delta_0 e^{-\lambda\delta} - (P + \frac{1}{\lambda})e^{-\lambda P} + P}{1 - e^{-\lambda P}} \qquad (9)$$

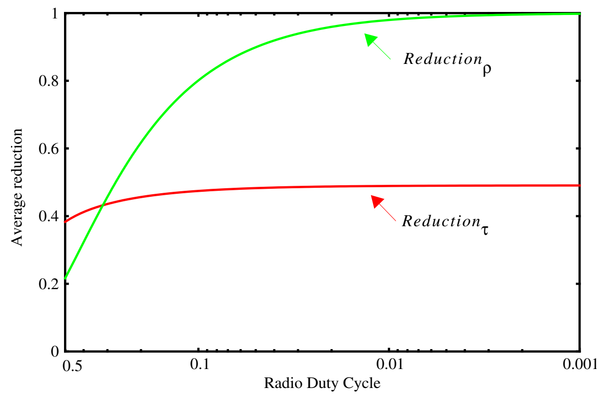

Figure 5. Average reduction of transmitter sending time ($Reduction_\tau$) and radio activation time at receiver($Reduction_\rho$) versus radio duty cycle.

The reduction of radio activation time at the receiver is expressed as:

$$Reduction_\rho = 1 - \frac{E_{framelet}(\rho)}{E_{long}(\rho)} \qquad (10)$$

Fig. 5 plots $Reduction_\rho$ as a function of radio duty cycle for normal parameters used in the implementation of the framelets approach for the DSYS25 sensor platform (δ=1ms, δ_0=9ms, Δ=15ms). The message arrival rate is one message per nine radio duty cycles ($\lambda = 1/9P$).

4.2. Interleaving Throughput

The maximum throughput at the receiver when communication takes place using the long frame rendezvous approach is at most one message per duty cycle period or

$$Throughput_{long} = \frac{1}{P} \qquad (11)$$

In fact, if two or more transceivers attempt transmission in the same duty cycle period, only one or zero messages can be received due to collisions.

The maximum receiver throughput using framelets is potentially higher, given that framelets can be interleaved. Assume transmitters can detect if the channel is busy and, in case it is, schedule their transmission no later than σ units of time after the end of transmission present in the channel. In this case, the maximum receiver throughput is:

$$Throughput_{framelet} = \frac{1 + \left\lfloor \frac{\delta_0}{\sigma+\delta} \right\rfloor}{P} \qquad (12)$$

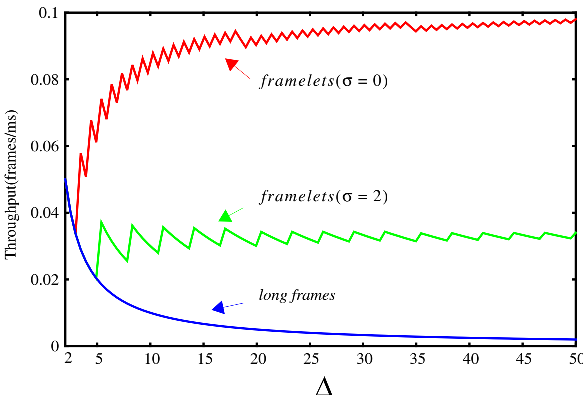

Figure 6. Maximum receiver throughput versus Δ, assuming duty cycle is fixed at 10%

If $\Delta = 2 \cdot \delta + \delta_0$, which is the minimum value according to inequality 1, then equation 12 can be rewritten as a function of Δ. Fig. 6 depicts the maximum receiver throughput for both rendezvous schemes as a function of Δ for δ=1ms and assuming the radio duty cycle fixed at 10%. The throughput for the framelets technique is plotted for two values of σ, with σ=0 being the maximum theoretical throughput.

The price paid for increased throughput, as the value of δ_0 increases, is larger transmission delays given that the duty cycle period $P = \Delta + \Delta_0$ also increases (even though the ratio $\Delta/\Delta + \Delta_0$ remains 10%).

5. Protocol Implementation

5.1. Platform

The DSYS25[3] sensor platform from University College Cork was used as the development platform and testbed for the concepts presented in this paper. The DSYS25 basic modules are comprised of an Atmel AVR ATMEGA 128 microcontroller and a Nordic nRF2401 transceiver [1]. Other functionalities, such as sensing, are added by stacking layers to the basic unit.

The transceiver is able to operate in Shockburst mode. This uses on-chip FIFO to clock in bits at a low data rate and transmit them at a very high rate in a fixed length packet of at most 256 bits. Putting all high speed signal processing related to RF protocols into the nRF2401 reduces current consumption, lowers system cost (by facilitating the use of a less expensive microcontroller), and greatly reduces the risk of on-air collisions due to short (high speed) transmission time. In essence, the transceiver enables/enforces a framelet approach in the link layer.

5.2. Implementation of the Rendezvous Mechanism

The framelet rendezvous mechanism with data replicas, acknowledgments and fragmentation described in Section 3 was implemented in the DSYS25 sensor platform. The code was designed as part of a TinyOS tailored version for the DSYS25 module. TinyOS[5] is an operating system designed at UC Berkeley and engineered to run in hardware platforms with severe resource constraints.

In its default configuration, each module operates at a radio duty cycle of 10%. The radio transmits packets of 256 bits at a speed of 250Kb/s. Therefore, the framelet transmission time δ is 1ms. The value of δ_0 was determined empirically and equals 9ms. Such a high value for δ_0 derives from two factors: acknowledgment of individual framelets and the Nordic nRF2401 radio requirement of re-clocking in framelet replicas as the radio empties its buffer after each transmission.

The active portion of duty cycle Δ was defined to observe inequality 1. The minimum possible value would be 11ms, but a slack of 4ms was added to overcome problems that could arise from jitter. Therefore, Δ=15ms. For a duty cycle of 10%, Δ_0 assumes the value of 135ms. Finally, the number of framelet retransmissions n was computed as the minimum value allowed by inequality 2.

The default configuration prevents interleaving. A transmitter senses the channel for a period equal to Δ before sending a message. If there is any activity in the channel, the transmitter backs-off a random amount of time before probing the channel again.

A second implementation of the framelet rendezvous scheme allows interleaving. In this implementation, transmitters send message immediately without probing the channel.

6. Experimental Evaluation

The platform and implementation of the framelet approach as it is described in the previous section is used for the experimental evaluation. The objective is to verify in practice the analytical results of Section 4. The evaluation comprises two experiments to assess energy savings and interleaving throughput as detailed next.

6.1. Experiments

The setup used in the experiments consists of a three-node network where two sensors act as a source and one operates as a sink. Sources generate and transmit messages to the sink periodically according to a Poisson distribution. A duty cycle of 10% is imposed on the sink's radio. The topology is simple, but able to capture the desired characteristics of the rendezvous techniques.

Energy Savings Experiment. The goal of this experiment is to verify in practice the analytical results obtained in Section 4 related to energy savings.

In order to achieve this goal, the implementation of the framelet approach described in Section 5 was compared against a long preamble rendezvous scheme adjusted to the DSYS25 platform. As the transceiver of the platform is packet based with a small size limit, long preambles are not possible and thus an emulation of the scheme was implemented. The emulation consists of a trail of beacon packets followed by a packet containing the data to be transmitted. If the receiver captures a beacon packet, it extends its listening period until the data packet is received. In this experiment only source 1 generates traffic.

The energy consumption per *message transmitted* is assessed by the number of packets (framelets) a transmitter sends when communicating the message. This metric is correlated with the transmitter sending time τ defined in Section 4.1. Similarly, the energy consumption per *message received* is measured by the number of message packets (framelets) captured at the receiver. This metric is equivalent to the radio activation time at receiver ρ defined in Section 4.1.

The results obtained by the described experiment and the corresponding analytical investigation (see Section 4) are shown in Table 1. For each point in the table, 10 independent tests are conducted and the results obtained are averaged. In each test, 200 messages are sent by the source. Messages are not fragmented.

As indicated in Table 1, the experimental and analytical results are close for the energy consumption reduction achieved by the framelet approach over the long preamble scheme.

Interleaving Throughput. The goal of this experiment is to investigate the possible throughput gain that can be achieved by interleaving in a practical environment (see Section 4).

Implementations of the framelet approach with and without interleaving were compared. In this experiment both sources 1 and 2 transmit messages at an average rate of one message per 180ms (according to a Poisson distribution). Thus, the transmission rate of one node is close to but below the theoretical channel capacity of 1 message per 150ms defined by the duty cycle period of 150ms. Framelet acknowledgments are not used in the experiment.

Theoretically, if no interleaving is allowed, close to

	Rendezvous variation		Reduction (Experimental)	Reduction (Analytical)
	#1	#2	1-(#1/#2)	
Energy consumption per message transmitted	7.12	15	52%	43%
Energy consumption per message received	1	7.79	87%	80%

Table 1. Energy consumption per message transmitted/received

	Interleaving #1	No Interleaving #2	Increase #1/#2
Delivery rate (Experimental)	0.61	0.47	30%
Delivery rate (Theoretical)	1	0.5	50%

Table 2. Receiver delivery rate for the framelet rendezvous approach with and without interleaving

50% of the messages should be delivered to the sink. In this case, two sources with a packet rate close to maximum available channel bandwidth compete for the media. If interleaving is allowed, 100% of the messages can be delivered to the sink. In fact, according to Equation 12, 10 sources would be able to use the channel at the same time.

As shown in Table 2, the delivery rate without interleaving is around 50%. When interleaving is allowed, the delivery rate change from 0.47 to 0.61, a 30% increase. This number is less than expected. This is due to the hardware limitations of the used nRF2401 radio. The microcontroller needs time to empty the buffer of the nRF2401. During this time period, no additional incoming frames can be received. Thus, some interleaved frames are lost at the receiver side. This fact explains why the interleaving success rate is reduced. However, the experiments show that the throughput can be increased by using interleaving techniques.

6.2. Discussion

The described experiments demonstrate in practice the energy benefits of employing a trail of framelets to achieve rendezvous over the use of long frames. Such benefits derive from the ability of reacting early to communication events. In particular, the use of acknowledgments frees the transmitter from having to send blindly a fixed amount of frame replicas to ensure rendezvous. As soon as the first frame is acknowledged, new frames can be scheduled for transmission. Furthermore, the use of data replicas spares the receiver from unnecessarily extending the active period of duty cycle for the reception of the first bits of data or for deciding whether the frame is addressed to a different node. This capability to decide early if a frame is addressed to a different node has the potential of significantly reducing the overhead caused by overhearing

The results also indicate that interleaving is able to improve the receiver throughput in practice when multiple transmitters contend for the medium.

7. Related Work

Several media access control protocols have been proposed addressing the issue of energy spent in idle listening through synchronous rendezvous techniques. B-MAC [8] for instance is a contention-based protocol that adopts a fixed duty cycle rendezvous strategy in which packets have long preambles. SMAC [10] uses a combination of duty cycle and shared-time strategies to establish rendezvous between transmitter and receiver. According to this scheme, nodes define a periodic fixed duty cycle and communicate it to its neighbors. Transmitters therefore know when a potential receiver will be awake and can schedule transmission at the correct instant. μ-MAC [4] is a schedule-based protocol and thus employs a pure shared-time rendezvous approach.

A more generic discussion of a rendezvous scheme, detached from any specific MAC protocols, is found in [9]. The technique proposed, called STEM, imposes a fixed radio duty cycle on nodes. A transmitter sends a sequence of beacon packets to the node it wants to wake-up. After a beckon is received, the receiver's radio stays on until communication is concluded. [6] proposes a related approach and compares it with a receiver initiated beacon scheme. Both STEM and the approaches in [6] are framelet-like since rendezvous is achieved through a trail of short packets. However, these papers do not explore the design space of framelet based rendezvous techniques. The beacons transmitted for rendezvous are control packets and interleaving is not discussed. Besides, no experimental data with real devices is presented.

The use of low-power wake-up radios to establish rendezvous between transmitters and receiver is discussed in [7]. Wake-up radios are the technique of choice in systems with low-load where a high level of responsiveness is required. Their main disadvantage is the need of extra hardware and limited communication range.

The demand for standards in the area of low-power networking prompted the creation of the IEEE 802.15.4 [2]. This standard addresses applications with relaxed throughput and latency requirements while favoring a low-cost and low-power design. IEEE 802.15.4 covers both the physical and MAC layer. Physical packets of at most 133 bytes can be transmitted at a speed of 250Kb/s. Preambles are 4 bytes long. Such characteristics make this standard suitable for the implementation of framelet approaches in contrast with long packet rendezvous schemes.

8. Conclusions and Future Work

This paper investigated the use of framelets - small, fixed sized frames - to achieve transmitter-receiver rendezvous and contrasts this technique with the use of long frames. The benefits of applying framelets were assessed analytically and an implementation of the concept for the DSYS25 sensor platform was presented and evaluated. The results showed that substantial energy savings can be achieved with framelets as well as an increase in communication throughput

There are several aspects of the framelet approach that were not explored in this paper and are left for future work. Reliability of data delivery was not assessed for the framelet technique. It is expected, however, that multiple retransmissions of data replicas increase the overall data delivery reliability in the presence of lossy channels. Another important aspect deserving further analysis is the definition of effective interleaving techniques. Finally, as the efficiency of the framelet scheme is highly dependent on the radio technology, an implementation of the approach in a different transceiver is planned. The nRF2401 Nordic radio, for instance, is unable to store packets between retransmissions. Packets need to be reloaded after each replica transmission, decreasing the efficiency of the framelet implementation. The Chipcon CC2420 ZigBee-ready RF transceiver on the other hand is able to buffer packets between retransmissions. It also has several built-in features, such as automatic generation of acknowledgments.

9. Acknowledgments

The support of the Informatics Research Initiative of Enterprise Ireland is gratefully acknowledged.

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