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Performance analysis of wireless sensor networks

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Abstract

This work focuses on the performance analysis of parallel bidirectional periodic peer-to-peer communication using IEEE 802.15.4 communication. The IEEE 802.15.4 communication standard forms the basis of popular communication protocols for wireless mesh networks such as the ZigBee specification, which received remarkable attention in recent years because of the growing popularity of the Internet of Things. The high rate bidirectional periodic data transfer is a commonly used traffic type in many applications on these networks, such as closed-loop networked control, sensor monitoring, and audio or video transmission. A distributed approach based on the packets received was used to monitor the performance indicators (jitter and packet loss rate) of the peer-to-peer communication in every communication node. As a performance analysis we carried out practical measurements in different cases: with and without ACK; different packet size and period; with and without parallel competitive traffic. Based on the practical results we proposed a parallel data transmission technique that increases the throughput of the sensor network.

Keywords: IEEE 802.15.4; sensor networks; mesh; performance analysis; periodic traffic;

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1. Introduction

With the popularity of the Internet of Things on the rise, sensor networks have received an increasing attention in information technology. Thus grows the need for low energy consumption wireless personal area networks to realize flexible, reliable and low-cost infrastructures.

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The IEEE 802.15.4 standard specifies the physical layer and the media access control for low-rate wireless personal area networks [1] which forms the basis of popular communication protocols for wireless mesh networks such as the ZigBee specification [2]. The main advantage of these networks (grids) is that they can transmit packets over long distances with low power consumption by passing the packets through intermediate nodes of the grid.

The physical layer (PHY) of the IEEE 802.15 was intended to use standard free wireless frequencies for communication, like 868 MHz with 20 Kbps throughput, 915 MHz with 40 Kbps throughput and the highest, 2450 MHz with 250 Kbps throughput. The standard separates the available frequency bands into a total of 27 channels (16 channels are available in the 2450 MHz band, 10 in the 915 MHz band, and 1 in the 868 MHz band) to ensure a reliable parallel communication. The MAC sublayer handles the access to the physical radio channel. This sublayer applies the CSMA/CA mechanism for channel access, manages the beacon and provides the GTS (Guaranteed Time Slots) mechanism. It also supports PAN association and disassociation, as well as device security and it provides a reliable link between two peer MAC entities. The IEEE 802.15.4 applies two types of channel access mechanisms depending on the network configuration: nonbeacon-enabled mode and beacon-enabled mode. Nonbeacon-enabled networks use an unslotted CSMA/CA mechanism while beacon-enabled networks use a slotted CSMA/CA for channel access [1].

This work focuses on the bidirectional peer-to-peer communication between pairs of nodes of an IEEE 802.15.4 network in nonbeacon-enabled mode. This working mode is supported by the majority of the commercially distributed IEEE 802.15.4 modules, including the basic models, providing simple to configure and low cost sensor network installations. The main goal is the analysis of the capabilities of the IEEE 802.15.4 networks for high rate bidirectional periodic data transfers, which are widely used traffic types in many applications on these networks, like closed-loop networked control, sensor monitoring, and audio or video transmission. The performance analysis is carried out with practical measurements in a real environment by testing different communication parameters and conditions.

These types of networks have received remarkable attention in recent years. Many papers focus on the analytical modeling, the performance analysis or the application fields of the IEEE 802.15.4 networks. A survey of wireless sensor networks is presented in [3] which emphasizes the importance of the IEEE 802.15.4 and Zigbee standards. In [4] a comprehensive mathematical model is presented for the MSK-modulated transmissions used to study the parameters affecting the performance of the communication. The authors of [5] propose an analytical evaluation method for saturated and unsaturated periodic traffic based on the analysis of Bianchi for IEEE 802.11 DCF using a per-user Markov model. A comprehensive study of the IEEE 802.15.4 and ZigBee standards is presented in [6] that is based on simulations performed with the NS2 simulator. Paper [7] presents the results of the analysis of the limits of the CSMA/CA mechanism used in the IEEE 802.15.4 in beacon-enabled mode for broadcast transmissions in wireless sensor networks. Paper [8] investigates the feasibility of Zigbee-like networks for low-rate voice streaming applications used in distributed surveillance, emergencies and rescue operations. In [9] a neuro-fuzzy approach for variable bit rate video transmission over ZigBee is proposed.

2. System description

For the practical experiments several pairs of XBee 802.11.5 S1 modules were used with 2.4 GHz working frequency and up to 250 Kbps transfer rate in transparent mode. The transparent mode of this type of module provides a byte stream transmission based on an initial configuration, without the need of communication management. This series of modules does not support the coordinator mode, so only the nonbeacon-enabled unslotted CSMA/CA mode is available for media access control. In this configuration the packet sending consists of the following steps (as described in [1], section 7.5.1.4):

- Perform backoff delay for a random number of complete backoff periods in the range 0 to $2^{BE} – 1$, where BE is the backoff exponent.
- Perform Clear Channel Assessment (CCA).
- Transmit if CCA is clear, otherwise BE = min(BE - 1, *macMaxBE*) and repeat steps 1-3 up to *macMaxCSMABackoffs* times.

Depending on the configuration and the packet type (non broadcast packet) a successfully sent packet can be confirmed with acknowledgement (ACK) packets (see [1], section 7.5.6.4). In this case the aforementioned algorithm is completed with two more steps:

- Wait *macAckWaitDuration* time for ACK from destination node.
- Done if ACK is received, otherwise repeat steps 1-4 up to *macMaxFrameRetries* times.

The aforementioned parameters of the XBee 802.15.4 S1 modem are shown in Table 1. [10] [11].

Table 1. The parameters of the XBee 802.14.4 S1 modem.

Name	Value
Backoff period unit	0.320 ms
macMaxBE	16
CCA time	0.128 ms
macMaxCSMABackoffs	4
macAckWaitDuration	0.864 ms
macMaxFrameRetries	3 + RR, where RR is the number of retries in addition to the 3 retries provided by the 802.15.4 MAC, by default 0.
Bit transmit time	4 us

Based on this information and knowing that every packet sent with 16 bit addresses has a header of 13 B, the time required for a packet transmission can be calculated as follows:

$$T_{transmit} = \sum_{s=1}^{\mathrm{try}_{\mathrm{send}}} \left(T_{air} + T_{CSMA}\right) \tag{1}$$

where n is the number of bytes in the packet.

$$T_{air} = (13+n)\cdot 0.032 \ [ms] \tag{2}$$

$$T_{CSMA} = \sum_{BE=1}^{\mathrm{try}_{\mathrm{CCA}}} \left[\left(2^{BE}-1\right)\cdot 0.320 + T_{CCA}\right] \ [ms] \tag{3}$$

Using equations (1), (2) and (3) the best and worst case transmission times of a packet can be calculated as follows for the XBee 802.15.4 S1 modem with default configuration:

$$T_{best} = 0.416 + 0.032\cdot n + 0 + 0.128 = 0.544 + 0.032\cdot n \ [ms] \tag{4}$$

$$\begin{aligned} T_{worst} &= (0.416 + 0.032\cdot n)\cdot 4 + (0 + 0.320 + 0.640 + 0.960) + 0.128\cdot 4 + 0.864\cdot 3 = \\ &= 6.688 + 0.128\cdot n \ [ms] \end{aligned} \tag{5}$$

The architecture of the system used for practical experiments is represented in Fig 1.

In every communication node the XBee 802.15.4 S1 module is attached with an XBee Shield to an Arduino Uno development board which runs the communication software, generates, sends, receives and parses the packets from the XBee 802.15.4 modems, and computes and sends the statistics information through a USB-RS232 interface to a computer, which runs the statistics software. The USB-RS232 interfaces and the personal computers with statistics software are optional components in the system and are only used to transfer and display the statistics results in graphical mode on the computer.

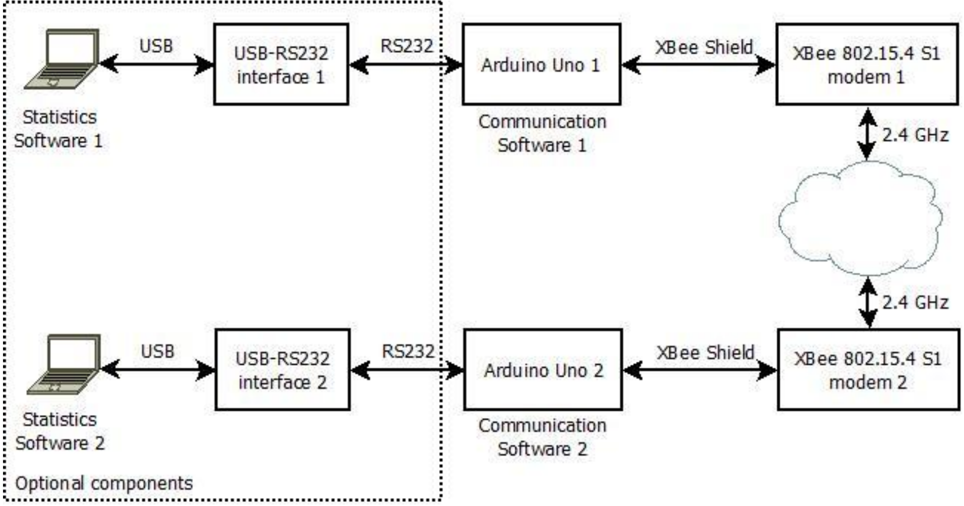


Fig. 1. System architecture.

3. Performance assessment methods

To monitor the performance of the peer-to-peer communication in an IEEE 802.15.4 network we use a distributed approach to measure the performance in every communication node based on the packets received. In order to measure the performance indicators on the application layer in the Arduino Uno sketch, a header is attached to every packet sent which contains the send timestamp of the packet and an incremental sequence number.

The main advantage of the Arduino Uno development boards in the system is that they provide an 8 us resolution for time measurement operations, allowing for high precision performance measurements.

Using this information the packet loss rate and the receive jitter can be calculated on the receiver’s side.

The number of packets lost between the last two packets received can be calculated using the sequence number from the attached header with equation (6).

$$loss[k] = seq[k] - seq[k-1] \tag{6}$$

The receive jitter represents the deviation from the periodicity of the received packet and can be calculated using the receive timestamps and the sending period of the received packets. The value of the jitter measured on periodic IEEE 802.15.4 channels reflects the number of retransmissions of the received packet in acknowledge-activated mode. The receive jitter can be calculated with equation (7).

$$jitter[k] = t_r[k] - t_r[k-1] - T \tag{7}$$

where T is the send period.

$$T = t_s[k] - t_s[k-1] \tag{8}$$

The packet loss and the jitter can be expressed in a single measured value if T is considered constant in equation (7).

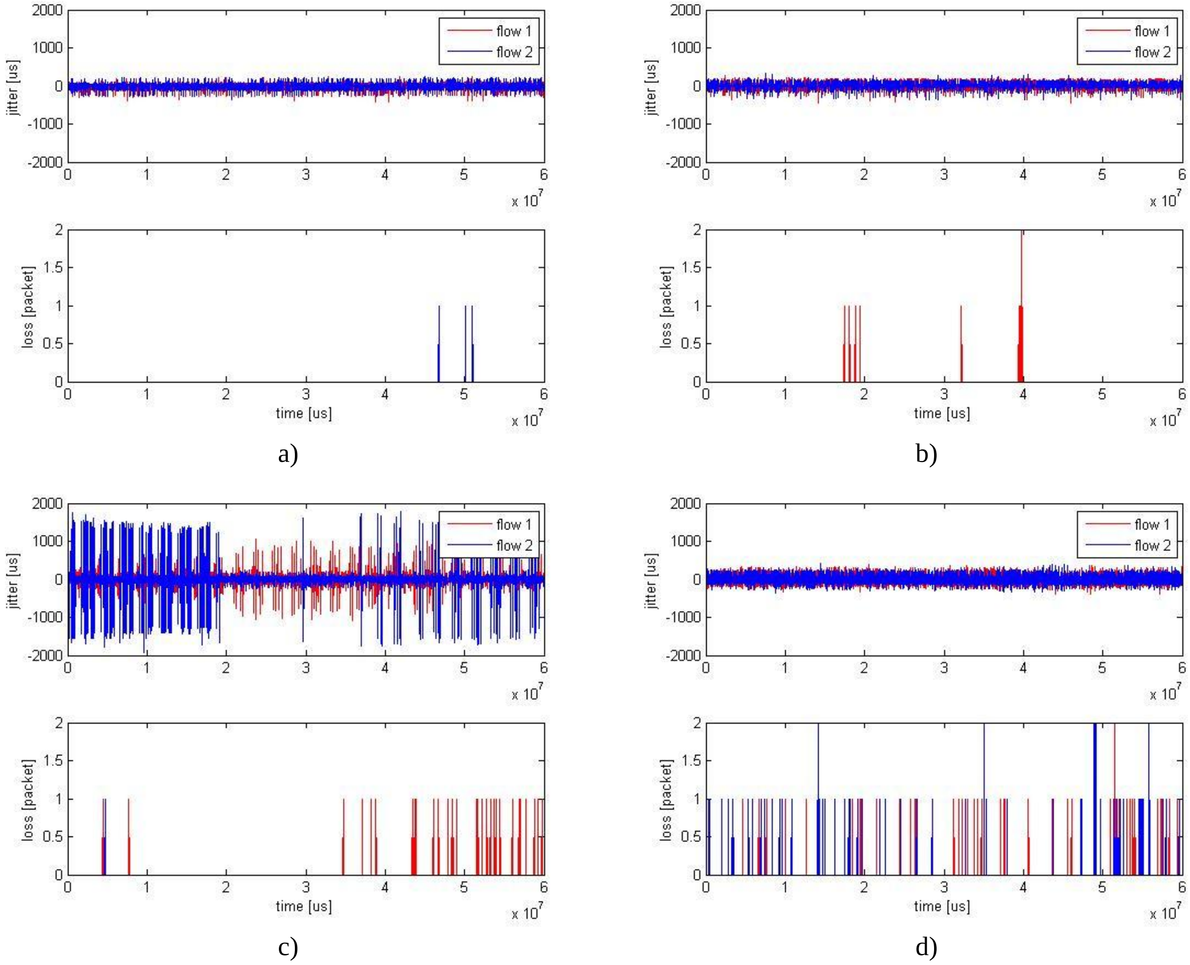
4. Practical performance evaluation of the IEEE 802.15.4 communication

In the case of huge sensor networks, because of the limited number of available frequency channels, parallel communications sometimes have to be performed on the same channel. The main goal of the practical experiments is to analyze the performance of the peer-to-peer IEEE 802.15.4 communication on the same frequency channel by monitoring the time variation (jitter) and the packet loss rate for parallel periodic data traffic in different cases: with and without ACK; different packet size and period; with and without parallel competitive traffic.

Equations (4) and (5) give an indication for selecting the sending period of the data flows for different packet sizes, for example for the 100 B sized (maximum in case of IEEE 802.15.4 modem) periodic packets the minimum sending period has to be chosen from the [3.744 ms, 19.488 ms] interval.

In the first phase of performance evaluation, practical measurements were carried out with two parallel (bidirectional) data traffics on the same channel of the IEEE 802.15.4 network with the packet size and sending period gradually increased and decreased respectively, with both ACK disabled and enabled configurations.

The measurements show that in ACK disabled mode good communication performance can be achieved on equal 30 ms period for both channel with 30, 50 and 70 B sized packets, but by increasing the packet size also moderately increases the receive jitter and the packet loss rate (Fig. 2. a, b, c). For 30 B packets also the 15 ms period is achievable, but in this case the communication suffers an increased, but acceptable packet loss rate (Fig. 2. d).



a)

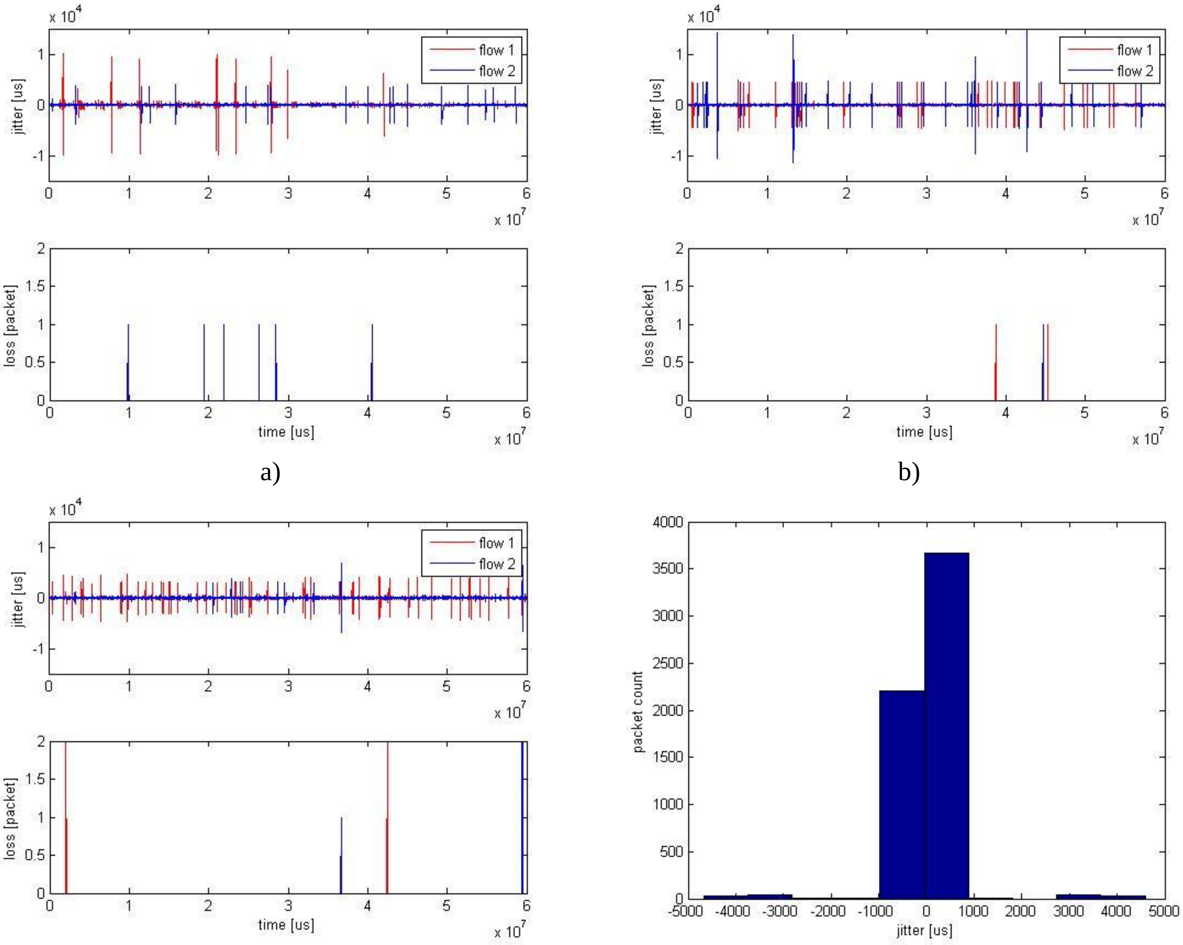
b)

c)

d)

Fig. 2. Communication performance in ACK disabled mode with a) 30 ms period 30 byte packet size b) 30 ms period 50 byte packet size c) 30 ms period 70 byte packet size and d) 15 ms period 30 byte packet size.

The same conditions can be achieved in ACK enabled mode with the previously used parameters. In this case the packet loss rate is significantly decreased by the retransmissions, but the side effect of the retransmissions is the high jitter and jitter variation. The packet retransmissions appear in the measured receive jitters in the form of up to 10 fold increases (see (1), (2) and (3)). Figure 3. a) and b) shows that the increase of the packet sizes also increase the retransmission rate, but the packet loss rate is not affected. The packet retransmission rate can also be increased by decreasing the sending period (Fig. 3. a and d). The histogram of the measured receive jitter shown in Fig. 3. d) highlights the number of packets transmitted on the first try (jitter between -1000 and 1000 us) and the number of packets transmitted with retransmission(s) (jitter with absolute value greater than 2000 us).



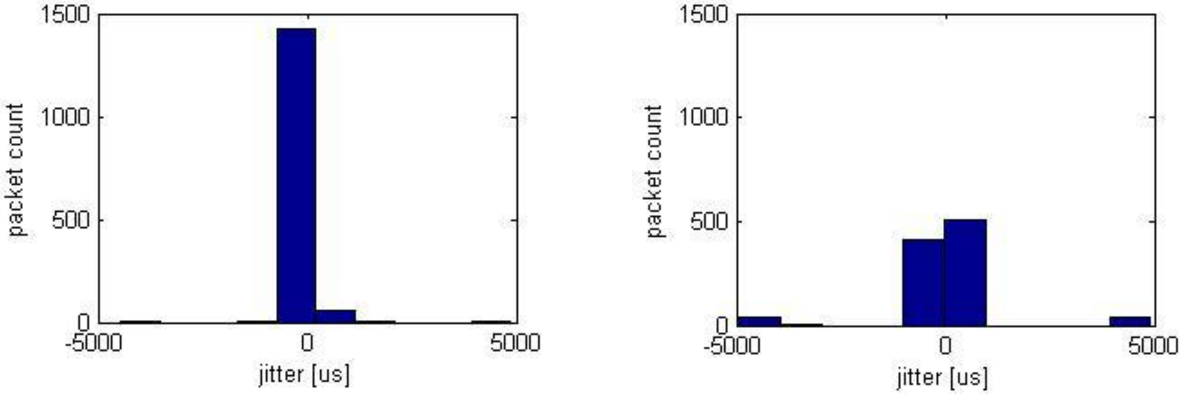
a) b)

c) d)

Fig. 3. Communication performance in ACK enabled mode with a) 30 ms period 30 B packet size b) 30 ms period 70 B packet size c) 15 ms period 30 B packet size and d) histogram of the jitter in the case of 15 ms period and 30 B packet size.

In the second phase we analyzed the effects on the communication performance when a second pair of periodic communication flow appears on the same frequency channel of the IEEE 802.15.4 communication medium.

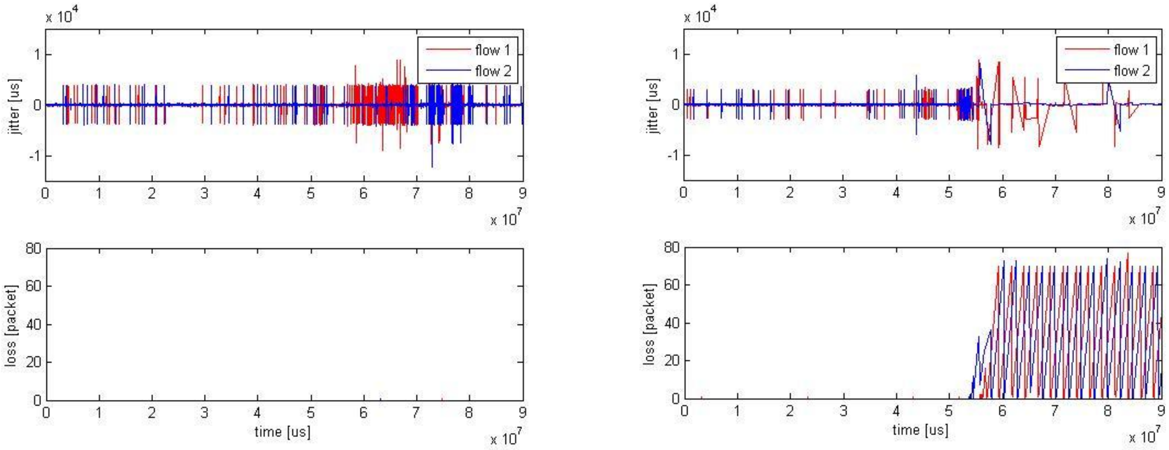
The practical measurements prove that a reliable communication performance can be achieved using two pairs of bidirectional periodic data flows on the same channel with 50 ms period and 20 B packet size. The addition of the second pair of communication nodes only affects the retransmission rate of the communication channels which can be extracted from the measured jitter values. From the histograms of the jitter in the case of one (Fig. 4. a) and two communication pairs (Fig. 4. b) it can be concluded that with the addition of the second communication pair the number of higher valued jitters grows, meaning that the retransmission rate grows.



a) b)

Fig. 4. The histogram of the jitter in the case of 50 ms period and 20 B packet size for a) one bidirectional periodic flow and for b) two parallel bidirectional periodic flows.

In the case of two pairs of communication nodes with bidirectional periodic traffic and different packet sizes per pair, the pair with the smallest packet size suffers a performance degradation as proved by the experimental results shown in Fig. 5. In these experiments in case a) two parallel periodic flows are started first with 30 ms period and 50 B packet size and after 50 s a second pair is started on the same communication channel with the same period but with 20 B packet size. In case b) the flow with a packet size of 20 B is started first and it is perturbed by a parallel competitive data flow with a packet size of 30 B.



a) b)

Fig. 5. Performance of two parallel bidirectional periodic data flows with 30 ms period and a) 50 B and b) 20 B packet size.

After analysing the measurements it can be stated that the highest throughput with the IEEE 802.15.4 communication with good communication performances can be achieved with a single pair of data flows (one in each direction) between two communication nodes with constant sending period and packet size.

Based on this conclusion we propose that in a complex sensor network that is based on the IEEE 802.15.4 communication standard, the parallel periodic data flows between two communication nodes should be sent as follows:

- Every periodic sensor data stream that is to be sent in a parallel manner has to be collected in the same sender communication node.

- The collected packets have to be fed in a single waiting queue.
- Packets have to be grouped and sent periodically from the waiting queue such that the prescribed packet size is achieved.
- On the receiver side the packets have to be separated into initial sensor data streams.

Using this parallel data transmission technique increases the throughput of the sensor network by avoiding the network performance degradations caused by the competition between the parallel data streams in interference. It also decreases the installation costs by reducing the number of communication modems that are required.

5. Conclusions

In this work we realized an extended performance analysis of real life scenarios for peer-to-peer communication between two nodes of a sensor network using the IEEE 802.15.4 communication standard. This was achieved by using a distributed approach to monitor the parameters in real time.

The measurements prove that the IEEE 802.15.4 standard provides a wireless communication mechanism which can be used for high frequency periodic bidirectional communication also in the presence of reduced or regular competitive parallel traffic, which can be used for closed loop control for example.

Based on the measurements we propose a data transmission technique that increases the throughput and the stability of the system as a whole.

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