Practical Remarks on Designing a Local Segment in a Wide-area Wireless Sensor Network for Measuring Factors Hazardous to the Environment

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***Abstract*—In order to construct an effective wide-area sensor network, an optimal solution consists in dividing it into a local and a core segment. On the local side, the ZigBee technology is commonly applied to transfer sensor data as it offers effective mechanisms of self-organization and automatic reorganization in case of failure. Since ZigBee is claimed to be natively suited to multi-hop transmission, its performance – in terms of throughput and delay – was quantitatively tested in a chain topology consisting of up to five hops. The achievable data rates were found to be exponentially decreasing with successive hops whereas the delay was growing linearly. A strong dependence was also confirmed between an antenna type used on ZigBee devices and the maximum achievable operating range.**

***Index Terms*—Mesh, multi-hop, IEEE 802.15.4, ZigBee.**

I. INTRODUCTION

Regardless of specificity of particular applications, in a most general form the purpose of a sensor network is to assure a bi-directional data transfer between the management center and multiple sensors scattered in various locations depending on a type of the monitored environmental phenomenon (more information can be found in [[1]]–[4]). The sensing range includes electromagnetic field (smog), noise (acoustic smog), organic and inorganic gases, industrial and biological waste (microbiological water control, gram-negative bacteria etc.). The final structure of the network, viewed not only as a transmission network but as a whole system for environment monitoring, is shown in fig. 1.

On the sensor side, the analog output signals are firstly adapted (in the Format Adaptation Module, or FAM) by means of sampling, digitizing and transmission frames construction, to the form acceptable by the ZigBee system underlying the local segments of the network (marked as ZigBee1-ZigBee3 in the figure). The signals are then passed in each ZigBee segment to one (or more) sinks – i.e. ZigBee modules equipped with a dual ZigBee/GPRS modem for transporting the data via a GSM/UMTS/LTE backhaul (the core segment in fig. 1).

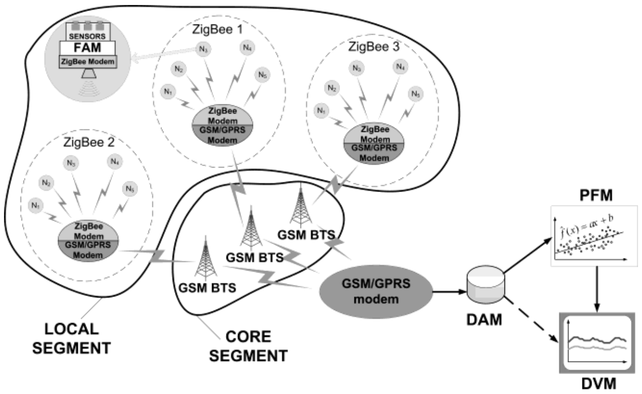

Fig. 1. A general structure of a complex wireless sensor network system.

Naturally, this scenario is not a universal solution but it ensures an almost unlimited extent of the sensing area due to a widespread coverage of nowadays cellular networks. The ease of deployment must also be appreciated since the sensor network operator is alleviated from the transport segment which is totally the issue of a cellular provider. On the other end of the network, the data collected from sensors with different frequency and volume, are gathered in fast, redundant and safe databases, called a Data Acquisition Module, or DAM. They can be further passed on to the Processing and Forecasting Module (PFM) for trends extraction, anomalies detection and forecasting the sensed phenomena behavior based on their measured history. Eventually, data can be either accessed directly (in their raw format) or through a Data Visualization Module (DVM) for the presentation of only some desired aspects according to the end-user's discretion.

II. LOCAL WSN SEGMENT – GENERAL CHARACTERISTIC

A wireless sensor network (WSN) is a set of sensors

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scattered on a given area. It should be noted that for the nodes to be autonomous parts of the network, their functionality must not only be limited to sensing capabilities but they are also expected to have a transceiver module and a power-supply source (most often – a battery). In fact, this problem is restricted to the local WSN segment, represented here by ZigBee technology (base on IEEE 802.15.4 specification [5]), and it is assumed that devices in this section are battery-powered. However it is also a critical segment in the WSN as it directly interfaces the sensor level. This makes things even more complicated from the energetic point of view since the available resources have to suffice for both the ZigBee radio module and the sensor. In the course of research the authors revealed a very mischievous feature of the sensing devices. Namely, as far as sensors for measuring basic air factors (such as temperature, humidity or pressure) are not very energy-consuming, the chemical sensors are. It is strongly associated with the principle of measurement they implement. They are catalytic sensors where the measurement is done by heating a sample (or even its incineration) to produce the target gas to be measured, as a product of such a reaction. Now, the heater is the real energy scavenger in this set-up, therefore for ZigBee-based networks, solar panels may sometimes be a solution of choice.

As for the transport segment, the powering issue is inherently resolved by using the cellular infrastructure. Returning to the local WSN issues, for quite obvious reasons it would be impractical (in many cases even impossible due to excessive distances) or energy-wasting to have the sensing modules send data directly to the sink node. Therefore, typically the information transmission in the local segment is realized by means of multiple hops between successive nodes. On the other hand, this procedure requires considerable traffic to be carried by intermediate nodes, which exploits their already limited energetic resources even further. A reasonable solution to this problem is to increase the number of sink nodes (i.e. nodes with a dual ZigBee/GPRS modem onboard) whose accumulators can be periodically recharged or some other form of power supply can be provided (such as solar panels). In this way the number of hops in WSN will decrease and so will the global energy consumption in the whole network by lowering the amount of transit traffic conveyed by ordinary nodes.

III. LOCAL WSN SEGMENT – CHOICE OF ANTENNAS

The issue of antenna selection, as opposed to cellular networks or other wide-range systems, is often understimated or over-generalized in WSN. The authors have investigated this problem by measuring the received power readouts on three sets of identical ZigBee boards with different antenna implementations: a rod antenna, a printed-circuit board (PCB) antenna and a microcontroller-embedded (μC) antenna [6]. In the measurement procedure the distance between two communicating devices was inceasing (as in fig. 2) until the connection was broken (i.e. the received power diminished below the threshold value, equal form -105 dBm to -110 dBm, depending on the device type).

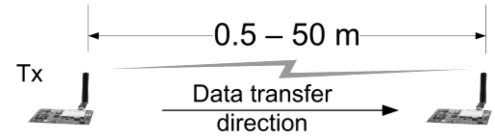

Fig. 2. A general structure of a complex wireless sensor network system.

As can be seen in fig. 3, the choice of a particular antenna solution will have a dramatic influence on the observed signal range: the longest with the rod antenna (i.e. 53 m) and the shortest with the microcontroller-embedded antenna (i.e. 22 m).

This results indicates that the convenience of no antenna protruding out of the device (which is the case with the microcontroller-antenna) comes at a considerable price of reduced effective range.

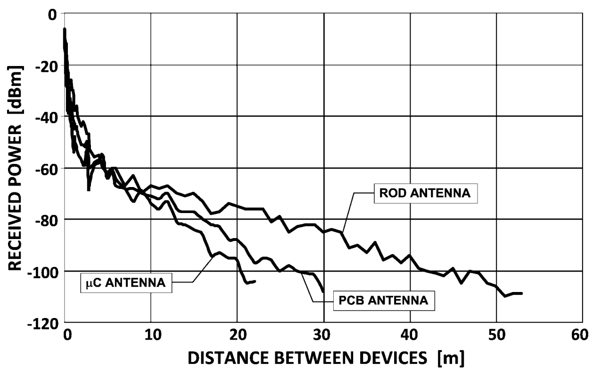

Fig. 3. Effective ZigBee range for different antenna types.

IV. LOCAL WSN SEGMENT – THROUGHPUT EFFICIENCY AND MULTIHOP TRANSMISSION

Another basic assumption of the ZigBee devices is their ability to operate in mesh topologies, which means that the data is likely to be transferred throughout the network via multiple hops. This, in turn implies throughput reduction with each hop since each intermediate device needs to participate in the medium access control routines upon each hop (let alone competing with other stations wishing also to communicate).

First of all let us examine the basic ZigBee frame structure, which is shown in fig. 4, in order to evaluate the first-order transmission efficiency. As can be seen, with the smallest signaling overhead (e.g. 4 bytes of Addressing Fields and no Auxiliary Security Header), there are n=118 bytes carrying the user‘s raw data whereas in the case with the largest overhead n=88 bytes. Since the maximum size of the whole frame is $SIZE$=133 B the throughput performance is already limited by the efficiency $\eta_{sig}=n/SIZE$ equal to 66% and 88% of the the maximum data rate of 250 kb/s envisaged by IEEE 802.15.4.

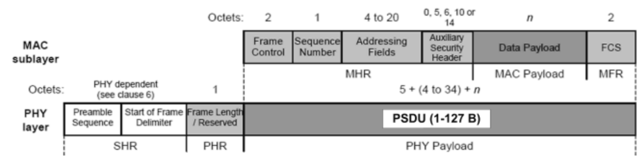

Fig. 4. A general frame structure of IEEE 802.15.4 (ZigBee).

As for the multihop transmission, an experiment was carried out with six devices connected in a chain and data transmission was run between Tx and Rx, as in fig. 5.

Two factors, crucial in data transmission process, were investigated, namely the achievable throughput and the delivery delay. Their dependence was observed as a function of the number of hops (within the range 1-5) and the packet size. The size was first set to 70 B and secondly to 90 B, whereby it was 10 B less or 10 B more, respectively, than the maximum 80 B per packet allowed by the producer. In fig. 6 it is clearly shown that the packet delivery delay is linearly dependent on the distance between devices, approximately 15 ms every 10 meters of distance.

As for the packet size, as the data were transmitted in 90 bytes long chunks, there was a need to send two packets per chunk – one fully filled with 80 bytes and the other to transfer the remaining 10 bytes (which means that the whole signalling overhead had to be added and transmitted as well).

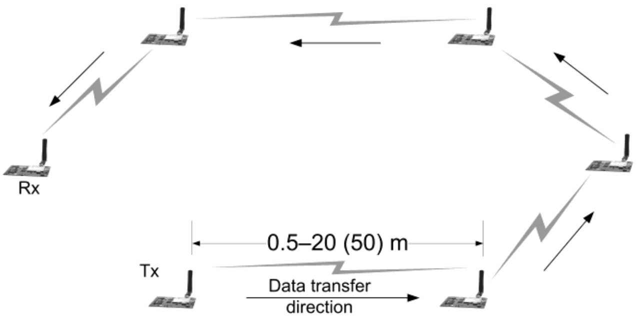

Fig. 5. The experimental setup: ZigBee devices connected in a chain topology.

This additional packet is apparently independent of the number of hops and the distance between devices, causing a constant average increase in delay of 9.5 ms. This result should be kept in mind when designing a sensor network in the local domain. The designer should program devices in such a way that single messages be multiples of maximum payload sizes. On the opposite side, one should avoid situations when this maximum is exceeded by a a little number of bits, which would require a whole new packet to be transmitted in order to carry this small portion of information, causing the 9.5 ms delay.

As concerns the effect that the number of hops has on the transmission delay, the results are presented in fig. 7. Here, regardless of the distance between devices, each successive hop adds an extra delay of c.a. 8.13 ms.

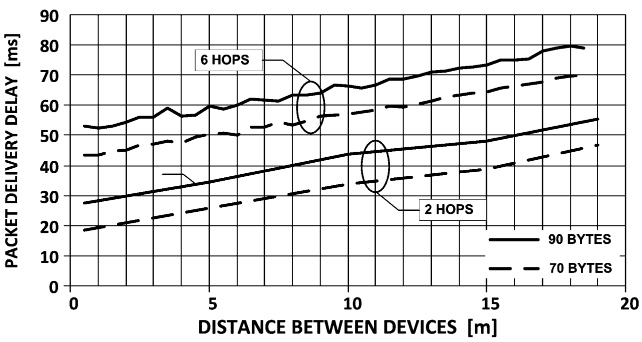

Fig. 6. The packet delivery delay as a function of distance between ZigBee devices.

Lastly, attention will be placed on the achievable throughput. Results of measurements are shown in fig. 8. The most significant observation is the peak throughput obtained for the most closely separated devices (the upper curve corresponding to the distance of 0.5 m). In the best case, as it appears, the ZigBee devices offer the throughput of little above 50 kb/s which decreases exponentially down to merely 20% of the initial value, as the transmission hops five times. With devices more further apart (like 10 or 19 m) the throughput degradation is not that drastic and the final value after five hops is still a few kb/s, but the initial throughput in point-to-point connection (i.e. one hop) is limited to only several kb/s.

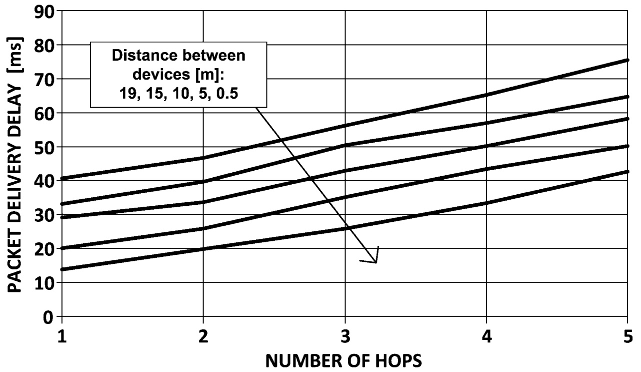

Fig. 7. The packet delivery delay as a function of the number of hops.

The positive side is that all curves flatten out and converge as the number of hops increases. This leads to assumption that in scenarios with even more hops, the guaranteed throghput, regardless of the separation between devices, will be on the order of a few kb/s. Fortunately, greater data rates are not necessarily required for sensoric data rates with only periodic or sporadic transmissions.

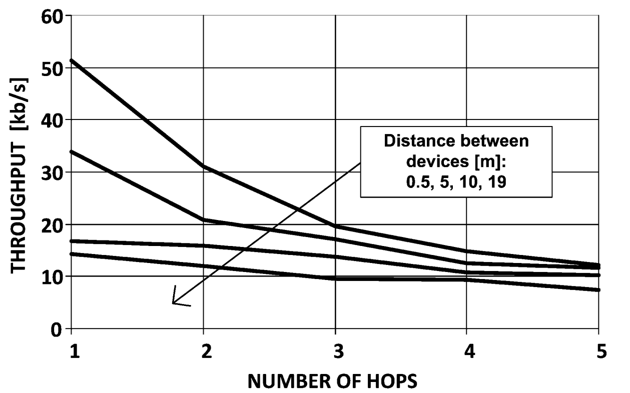

Fig. 8. The throughput decrease in ZigBee devices, as a function of the number of hops.

V. CONCLUSIONS

A general architecture of a wide-area sensor network is proposed in the paper, with a distinction of two major components: the local and the core segment. The investigations presented here are focused on the former and refer to the ZigBee technology as a natively suitable choice for interfacing with sensors and passing these data further on.

Firstly, the maximum operational range in meters was examined for ZigBee devices equipped with different antenna implementations. It turned out that the rod antenna (though more cumbersome in use) outperforms the two other solutions by allowing almost twice the distance achievable with the μC-embedded antenna.

The paper also discusses the results of experimental research on the performance of ZigBee devices operating in a chain topology. Such a setup is representative to a typical path traversed by packets in mesh networks where data from sensors are transmitted by proxy of multiple interconnected nodes (in a process called "a multi-hop transmission") that separate the source of the message from the sink. It was demonstrated that the maximum throughput is strongly dependent on the distance between nodes, although this dependence becomes less distinguishable with the number of hops. Moreover, the data rate declines exponentially with each successive hop, unlike the transmission delay which at the same time increases linearly. Lastly, it was observed that the delay is also affected by a degree to which the data payload (fig. 4) in a packet is filled.

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