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WIRELESS SENSOR NETWORK BASED OF IEEE802.15.4 WITH REAL TIME CAPABILITY

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ABSTRACT

The scope of this project is the development of the hardware and software basis for a wireless network, based on the standard IEEE802.15.4 and built up in a star network topology, to transmit data from remote sensors (RF-End Device) to a central processing unit (RF-Net Coordinator).

The main focuses are the real time capability of the system according to the timing requirements of the project, by using a Superframe structure with a so-called “contention-free period (CFP)” and „Guaranteed Time Slots (GTS)“ as described in IEEE802.15.4 [1], the robustness against interferences within the harsh RF environment of the widely used 2.4-GHz-band, the battery-powered operation of the sensors (and hence the energy budget) and the coexistence of several similar networks, even within the radio transmission range of a neighbouring system.

The primarily targeted sensor types are pressure and torque measuring devices, but the use of other sensors or different data sources may also be possible under consideration of the system’s maximum transferable data rates.

Index Terms **–** IEEE802.15.4, wireless sensor network, real time, guaranteed time slot, contention access period, contention free period, Superframe structure

1. INTRODUCTION

There is no “ideal wireless technology”, but rather a most suitable wireless technology for a clearly defined Application (Requirements). A lot of parameters or requirements, respectively, play a decisive role when choosing the suitable wireless technology: communication range, current consumption, concept of power supply (i.e. battery capacity), data rate, real time capability, data delay time, immunity to interferences, duty cycle, maximum transmission power, Norms, Standards, laws and provisions.

The wireless communication technology is not a new practice, but wireless solutions will be used more and more in the industry (i.e. iWLAN, wirelessHART, IEEE802.15.4), by home automation (i.e. ZigBee) and for many consumer products (i.e. WLAN, Bluetooth). Wireless products will replace wired solutions and will open new types of technical and economical solutions which seemed previously unattainable. The full potential of wireless technology is becoming more and more recognized and increasingly applied.

2. REQUIREMENTS AND CHOICE OF WIRELESS TECHNOLOGY

So why choosing the IEEE802.15.4-technology? The main goals of the project are the development and provision of the hard- and software basis for wireless connection of sensors with the following main features: real time capability (defined latency, deterministic behavior), safe operation in industrial environment (i.e. WLAN and Bluetooth interferences), battery operation (energy budget), simultaneous operation of multiple systems and a distance range of approx. 40 m indoors.

In principle, two different frequency ranges can be used: 868 MHz (for North America 915 MHz) and 2,4 GHz (quasi worldwide available). The Sensors work in two different modes.

At first there is the monitoring mode, where the sensor transmits a telegram every three seconds to confirm the correct function of communication and synchronization with the coordinator.

The second one is the measure mode. The measure mode is activated by the user several times per hour and always takes approximately five minutes. Over this time, the sensor operates effectively continuously under real-time conditions by sending sensor data. The maximum allowable data latency time should not exceed 100 ms (defined as real time requirements).

Note that the duty cycle is limited in the 868-MHz-Band (i.e. 1% in Band g1). That’s why this option is out of the question, although the operating distance in this frequency range is better.

If we consider the available technologies in the 2,4-GHz-Band, IEEE 802.11x WLAN, Bluetooth, IEEE 802.15.4/ZigBee, NanoNet und proprietary system products are mainly used. The energy needs of IEEE802.11x (WLAN) and Bluetooth compared with the energy consumption of IEEE802.15.4/ZigBee systems is relatively high and not so suitable for battery powered equipment. Furthermore, the focus of these systems is middle-range to high data rate. Hence these technologies have not been considered further.

Because real time systems are not supported by ZigBee (ZigBee is not providing corresponding services for the 802.15.4-GTS-options) we have chosen the realization based on the IEEE 802.15.4-standard [1] with a proprietary implementation of the higher layers.

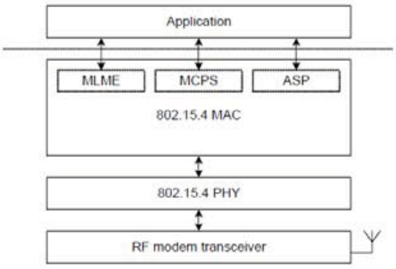

Figure 1 802.15.4 Software Stack [2]

The IEEE 802.15.4-stack offers various modes of operation. The modes are used for various purposes and requirements.

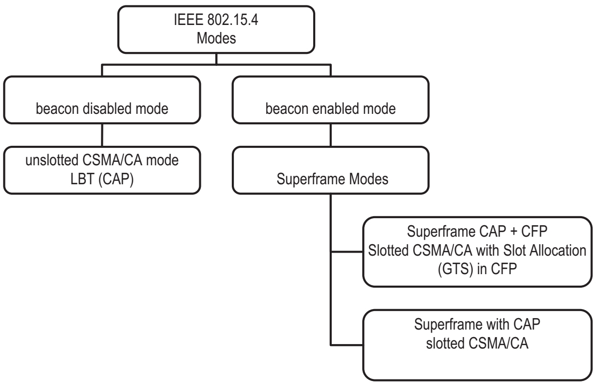

Figure 2 IEEE802.15.4 Modes

Only with the operating mode "beacon enabled mode" (superframe) with guaranteed time slot (GTS) allocation it will be possible to meet the needs for real time communication. Within a GTS an exclusive time-domain will be reserved for a defined network node.

3. IEEE 802.15.4, REAL TIME CAPABILITY AND TOPOLOGIE

The generic term "real time" is not to be equated with "without delay" or with ultra-fast system reaction, but it means a defined latency time or a deterministic time behavior, respectively, in this case. The latency time is to be understood here as the communication pending time from sensor data output to the sensor data processing unit (i.e. PC).

With the use of MeshNet topology, used very often in ZigBee systems, the latency time is non-deterministic and varies widely with the depth of hopping. Another conclusion is that the non slotted carrier sense multiple access with collision avoidance (CSMA/CA), defined in the 802.15.4-Standard for communication within the CAP, prevents real-time operations. The CSMA/CA-algorithm is useful for many application, but not for real-time systems. Also with a permanent integration of a repeater to extend the operating distance a deterministic time behavior could be realized, but the latency time is accordingly higher. This is not a native feature of the 802.15.4 standard (self-routing over different ways) and takes much higher efforts.

A disadvantage of the star topology is that it's not scalable. .But for realizing the real time requirements we have chosen the star topology for our project.

Another important issue is the sum of all physical data transmission times from the data source to the data destination. The sensor data is transmitted via UART (Sensor-Controller – RF-Module), followed by the RF-transmission (with GTS), CRC check and other data processing in the Coordinator. The Coordinator will forward the packet to the connected control unit (PC) via UART/USB. The bottleneck in this case is the limited interface between the Coordinator and the PC, because the data of all sensors must be send via this interface (max. five active and five passive sensors). In order to integrate the measurement data we will use a data protocol with 22 Byte (active) resp. 9 Byte (passive). This all adds up to a approx. 27,34 ms UART-Time (at 115.200 Baud data rate), or 21,9% of the superframe time.

4. SUPERFRAME, GTS, DATA RATES

The IEEE 802.15.4 offers via PHY a data rate of 250 kbps. However, if we consider the superframe structure with the embedded GTS, ACK frames and the interframe space time (IFS) for five active sensors, it is becoming obvious that the real payload data rate is much smaller than 250 kbps.

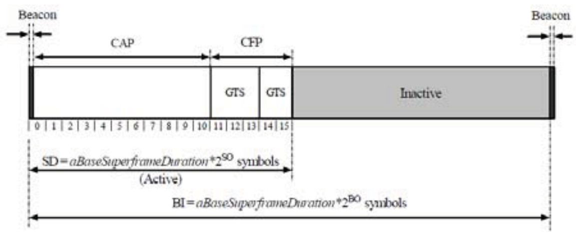

Figure 3 Superframe Structure

The settings of the superframe shall guarantee the max. latency time of 100 ms. Therefore a Beacon Interval (BI) smaller than 100 ms is necessary. There is no inactive period in the superframe structure, so the set value of Beacon Order (BO) and Superframe Order (SO) must be in range from 0 to 2. The active period in the superframe is divided into 16 equal parts (0 to 15), where the time slot 0 is reserved for the coordinator beacon. RF packets could be send by the associated sensors at the beginning of each time slot (from 1 to 15) in competition (CSMA/CA) within contention access period (CAP), if there are no GTS allocated. The CAP will be used for inactive sensors and is not qualified for real time communication.

There are up to seven GTS, the specified minimum time of CAP is 7,04 ms. So the selection of BO and SO is very limited.

BO	SO	BI	t_{Slot}/ms	GTS	t_{GTS}/ms
0	0	15,36	0,96	1	0,96
0	0	15,36	0,96	2	1,92
1	1	30,72	1,92	1	1,92
1	1	30,72	1,92	2	3,84
2	2	61,44	3,84	1	3,84
2	**2**	**61,44**	**3,84**	**2**	**7,68**
3	3	122,88	7,68	1	7,68
3	3	122,88	7,68	2	15,36

Settings with BO = SO = 0 are not possible, as well as settings with BO/SO >= 3, because the real time requirements (100 ms max. latency) cannot be met. We have chosen the settings BO = SO = 2, using two superframe time slots for GTS for each sensor device. A maximum of five independent sensor devices can send at quasi the same time within the GTS (measure mode, real time communication), five other devices will be allowed (monitoring mode) to send within the CAP. So a time of 7,68 ms will be reserved within every superframe for each of the five sensor devices for real time communication.

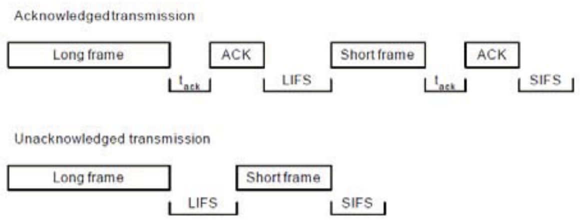

Figure 4 Communication structure with ACK and IFS

The GTS should be allocated by the sensors and will be administrated by net coordinator. Gaps within the GTS block are not permitted. If there is a GTS deallocation within the GTS block, all remaining GTS will be summarized at the end of the superframe without gaps.

Assuming the user data length is six bytes (payload), the time of communication is at minimum 2,4 ms with the consideration of the ACK packet from the coordinator (ACK without payload) and the long interframe space (LIFS). With a payload length of 102 bytes (max. payload) the total RF communication time needed is 5,47 ms. Without ACK (application specific) the channel is occupied only 1,82 ms (6 byte payload) resp. 4,9 ms (102 byte payload).

So up to three telegrams with six bytes payload or one telegram with 102 bytes payload can be send within the allocated GTS every 61,44 ms. In this constellation the given real time requirements (100 ms max. latency) will be met with sufficient reserves for retries (i.e. due to interferences).

The max. achievable real data rate (BO = SO = 2, GTS with two slots, five allocated GTS) reaches 13,28 kbps at 102 byte payload resp. 2,6 kbps at 20 byte payload for one RF-End Device.

These data rates are sufficient to achieve the real time requirements of this project. But if this project needs to be adopted to other systems with other requirements, the settings and the resulting data rates and other values should be noted.

5. OPERATING RANGE

The required RF range is 40 m indoors. In principle it is problematic to guarantee a RF range without giving measurement conditions. However, for the evaluation of the RF range a careful consideration of RF damping is necessary in advance.

Under ideal conditions (free space), the free space losses of the RF signal α is calculated as follows: $\alpha = 20 * \log_{10}(4 * \pi * d / \lambda)$, where λ is the wavelength of the carrier signal and d is the distance between the transmitting and receiving device. At a distance of 40 m the calculated free space loss is 72,09 dB (at 2,4 GHz). The path-loss-Model in [1], $pl(d) = 58.5 + 33 \log_{10}(d/8)$ for distances of more than eight meters, results in a path loss of 81,57 dB.

The factors, which determine the RF range, are the (limited) radiated power, the receiver sensitivity, the antenna gain (for Rx and Tx), the free space losses depending on the distance and frequency and additional damping, which is mainly due to reflections (multipath propagation), RF shadowing, absorption, diffraction and scattering etc. These effects can be found stronger indoors.

Even if there is a line of sight (LOS) connection some of the previously mentioned effects are still existent. If there are any obstacles placed directly in the line of sight or within the so-called Fresnel Zones between the transmitter and receiver, the range will be reduced.

The maximum radius b_{max} of the first Fresnel Zone can be calculated with the formula $b_{max} = 0,5 * \mathrm{sqrt}(\lambda * d)$. At a distance of 40 m (requirement) the maximum radius of the first Fresnel Zone is 1,12 m. For example, when half of the first Fresnel Zone is covered, the remaining field strength is reduced to the half (additional RF damping of 6 dB). For indoor applications this is a very important fact, because here the first Fresnel Zone is usually not free from any obstacles.

A RF range of 40 ms in industrial environments (working hall) is realizable with a static construction and favorable positioning of the Transceiver at all, but with changing conditions (mobile sensors) this cannot always be guaranteed.

6. SYSTEM ARCHITECTURE, SENSOR ARCHITECTURE

The following picture shows the architecture of the overall system. Four parallel sensor nets with a Coordinator (C) and up to 10 sensors (S) in a star topology. Up to five sensors can work in the active measuring mode. The Coordinators are connected with a higher system (PC), which handles the administration and the data processing.

Optionally, a remote control function of the nets can be also realized via the Internet connection of the PC.

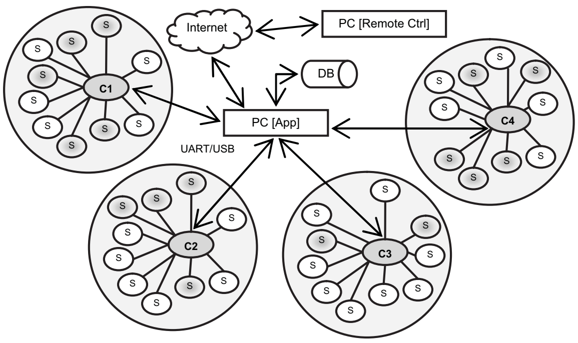

Figure 5 System Overview

The ideal demarcation of the several (radio) nets (cells) as shown in picture 5 will not be found in practice, where a stable operation of overlapping cells has to be guaranteed by choosing of distinct RF channels (frequency management).

A single sensor mainly consists of the physical sensor, the controller for the data processing, the RF module with antenna, power supply and various peripheral elements.

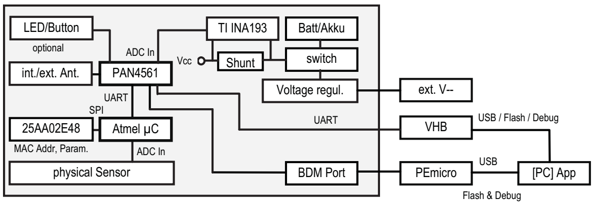

Figure 6 Net Node (End Device)

The Coordinator itself has no sensor systems. It is the central device of the communication infrastructure of a net, determines by the transmission of the Beacons the time framing (Superframe) and coordinates the different net activities like GTS-Allocation, Association and Disassociation of RF sensor devices, data transfer etc.

7. ENERGY BUDGET

The net nodes are battery-powered devices. That's why the energy budget plays an important role for the acceptance of the system to the customers.

Whereas the Coordinators are to be considered as less critical, because they are net-supplied. The energy consumption of the RF sensors can be separated from the user's point of view into the measuring mode (active mode) and the supervision mode (passive mode), or from a module approach roughly into the blocks sensor/controller and the 802.15.4 RF module PAN4561.

Description	Value
Tx Current PAN4561 (@10,1dBm)	118 mA
Rx Current PAN4561 (typ.)	48 mA
Idle Current	1 mA
BI	61,44 ms
Tx Time/BI (active Mode)	2,59 ms
Rx Time/BI (Beacon)	1,00 ms
Active mode time (a 5 min, 5/h) in 24 h	10 h
Passive mode time (other time) in 24 h	14 h
Power Requ. Active Mode pro 24h	67 mAh
Power Requ. Passive Mode pro 24h	26 mAh
Total Power Requirement pro 24h	93 mAh

Due to the quasi-continuous transmission in the measuring mode the demand for energy is not comparable to classical IEEE802.15.4/ZigBee applications with operation cycles of some years and seems to be quite high.

For industrial applications the operating durations are still acceptable, with respect to alternative technologies like Bluetooth or WLAN and when accounting for the advantages resulting from the wireless technology.

8. LATENCY

The maximum allowed latency time of the system is given with 100 ms, the BI is set to 61.44 ms (BO = SO = 2).

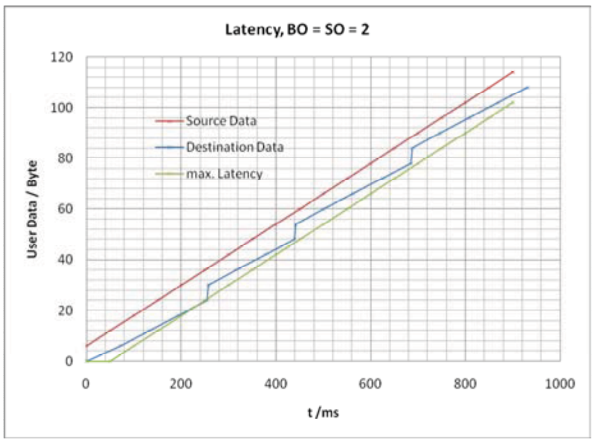

Figure 7 Latency Stages

Due to the cyclical transfer of the data it leads to a staircase transfer curve (Figure 7), wherein the steps may not cross the maximum allowable latency of the system. It can last up to 61.44 ms (beginning of the next GTS), before a generated record can be transferred. At the end of the GTS (7.68 ms length) the transfer must be concluded, including occasionally necessary repetitions of transmissions caused by interferences.

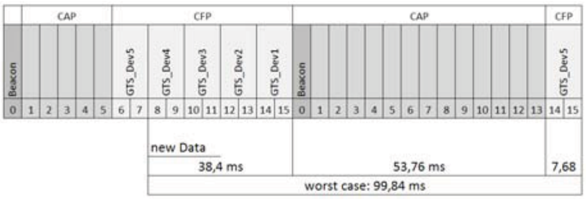

Figure 8 worst cace Latency

In worst case is to be assumed from the fact that immediately after the end of the GTS a new record should be transferred (i.e. Dev5). For example, in the slot 6 begins the allocation of GTS. By Disallocation of all other GTS the whole GTS block will be reallocated, the GTS of the device Dev5 begins in the next Superframe then in the slot 14. In this case the transference can be concluded only after 99.84 ms, close on the allowed border of 100 ms. However, this case will appear only in a few points within a measuring cycle.

Another point is the time after activation of the measuring cycle up to the beginning of the transference. Here a suitable delay is to be included in the plan for the allocation of the GTS.

9. INTERFERENCES

Exclusively to a sensor by allocation of GTS made available communication window (GTS) guarantee the real time transference within own PAN. Up to four in parallel pursued systems are pursued on other very far canals distant of each other (choice automatically by Band scan or administratively by users). Other systems like WLAN-, Bluetooth or proprietary systems can disturb the communication, however, under circumstances up to the complete malfunction.

There are a lot of investigations on the subject Interferences in the 2.4-GHz band (i.e. [3], [4], [5], [6], [7]). It is to be read that anyway of different perceptions, approaches, methods and tools are to be seen by the respective basic statement a clear trend. A generalized summary of the recommendations should be tried here:

a) Channel spacing

The exploitation of the at most possible frequency distance between 802.15.4-Systemen systems as well as systems which are based on other technologies (WLAN, Bluetooth, proprietary etc.) is recommended. With smaller RF bandwidth of the interference transmitter a bigger frequency distance is advised. The work on the same frequency should be avoided. The frequency offset between WLAN and 802.15.4 should amount to at least 30 MHz. With the 802.15.4 PHY/MAC tests on packet error rate (PER) as a function of the distance between WLAN and 802.15.4 as well as from the frequency offset between the systems becomes minimally 20 MHz of frequency offset recommended.

b) Distances

The greatest possible distance is to be chosen always to the interfering devices, always the smallest possible distance between transmitter and receiver. With distances to 1 m between WLAN and 802.15.4 a communication is barely possible from 802.15.4 practically, even with big canal distances. With overlapping canal a communication is only with ext. PA and 10 dBm and big distance (> 14 m) possibly. With distances of the WLAN from mind. 2 m and frequency distances between 802.15.4 and WLAN from mind. 25 MHz a transference of 802.15.4 telegrams of 80% is possible without temporal delay with 30 m of distance between the ZigBee devices (free space). The least distance of WLAN devices to 802.15.4 devices should amount to 2 m.

c) Duty Cycle

Enough "idle time" between the 802.11 RF packets is favorable, so that 802.15.4-Telegramme telegrams can be set down successfully. The data traffic of all sending systems should be limited to the necessary minimum measure.

d) Detection and reacting

Frequency agility, thus the frequency change (channel change) during the run time of the system is a basic quality in view of the reaction to interferences and should be implemented compelling. A careful Band scan for the canal choice is recommended. However, for the direct assessment left quality the pure RSSI measurement is not necessarily suitable.

e) Radiated power, receiver sensitivity, selectivity

Here play the order of the modules, the radiated power, the receiver sensitivity and the spatial radiation pattern a role. In general only the radiated power necessary for the application should be used always. The signal-to-noise ratio at least a relation of 20 dB is recommended.

f) Latency time

There are differences between MAC test level und NWK-/APP test level. With the NWK-/APP level test the packet error rate (PER) is mostly zero; the influence of the interferences appears almost exclusively in the rise of the latency times, because suitable provisions in the software stacks (like packet retries) reduce the risk of a real packet loss.

Interferences affect primarily the latency time. For many applications which do not depend on deterministic time behavior this is away practicable to realize robust communication also in very disturbed surroundings.

g) Management, Tests

Measurements should occur always in two real surroundings with typical WLAN systems. If there a time critical application, a management for coexistence is necessary. Procedures for decoupling (space, time, frequency) are important, a possible prohibition from mobile active Bluetooth or WLAN systems in the industrial sphere is to be checked.

Furthermore it can be found out that there are marginal analysis results to the interference potential from 802.11n (band width up to 40 MHz). By application of the systems which work on this standard the danger of interferences is incomparably higher. Indeed, with the frequency management can be provided, that to shift new WLAN systems in the 5-GHz band.

10. CONCLUSION

To sum up, with the IEEE 802.15.4 standard a real time transference is basically possible. Considering the interference problems and the limited real data rate the use of the 802.15.4 system is reasonable for many applications.

The interfaces between the sensor controller an RF module resp. RF module and higher system (PC) was implemented universally about UART with an open protocol extendable any time, so that a binding is possible to the most different data sources without a lot of expenditure.

About the variation of the parameters Beacon Order and Superframe Order other constellations are also possible with regard to benefit data rate, latency time and energy requirement.

The specific parameter settings can and must occur according to the requirements of the respective application.

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