Energy and Frequency Analysis of Wireless Smart Metering Solutions

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Abstract: **The aim of this paper is to provide a brief summary and analysis of today's state-of-the-art wireless smart metering solutions. The most important factors to evaluate wireless protocols are presented in order to form basics of further research. Furthermore a mathematical approach was constructed which determines numerically the efficiency of the evaluated systems. Using the created formulas, the efficiency of different smart metering solutions was calculated in bit/Joule. Also measurements were conducted to determine the available range using different frequencies.**

1. INTRODUCTION

Nowadays one of the very important areas in research and development is smart metering. More and more countries are introducing their own solutions for the task, as automated reading of data offers tremendous advantages over the conventional methods. European Union directives are motivating further research.

Possible application areas of the system: metering of gas, electricity, water etc. consumption in a remote and scalable way. The technology should be operable in villages, sparsely populated areas and also in blocks of flats in cities. These special criteria challenge device vendors because of the entirely different goals and needs.

The paper is structured as follows: Section 2 introduces smart metering advantages over traditional metering. Section 3 summarizes the available solutions suitable for wireless smart metering.

Section 4 compares the selected solutions based on a set of features. Section 5 introduces a novel calculation of protocol efficiency and compares the solutions according to the results. Section 6 presents the frequency versus range measurement conducted during the research. The last section concludes the paper.

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2. SMART METERING

Smart metering technology is supposed to substitute the traditional meters, practically by digitalizing them. Today's analogue meters can only measure the total consumption of a billing unit, which means there is no information about the exact values between two readings. In contrast, smart meters are able to determine e.g. the hourly consumption and identify differences between the different periods of a day, and present these data to the provider and consumer. This technology provides not only digital reading of meters but much more, for instance alerting functions. Smart metering devices can form a wireless network which collects and forwards every single device's measured data to a central unit for processing. With the help of smart meters the end users can monitor their current consumption (water, gas, electricity and also providers can obtain continuous information about their users' consumption customs.

Advantages for the provider are as follows:

- more accurate knowledge of the time distribution of measured data
- decrease of administrative costs
- monitoring of leaks continuously
- more opportunities for retail service renewal

Advantages for the consumer:

- no payment for meter reading and billing
- quick detection anomalies (broken pipes, gas leaks, etc.)
- consumption can be monitored real-time
- current balance can be monitored

According to Berg Insight's newest research, the number of households using smart meters will reach 130 million in Europe by 2015, and 116.5 million is Asia, Australia and the Pacific summed [1].

3. AVAILABLE SOLUTIONS

There are many wired and wireless solutions available, but this article focuses only on wireless technologies.

The following solutions passed our selection criteria:

DASH7 is a wireless sensor network technology based on active RFID standards (ISO/IEC 18000-7). The operating frequency is 433 MHz, which is in one of the ISM bands and can be used worldwide. The technology was originally developed for military use (supported by US Department of Defense), but it is penetrating to consumer markets as well.

The standard is being pushed by the DASH7 Alliance, a non-profit industrial syndicate existing since March 2009. OpenTag is an open source implementation in C language [2].

ZigBee is a specification for a suite of high level communication protocols using small, low-power digital radios based on the IEEE 802.15.4 standard for Low-Rate Wireless Personal Area Networks (LR-WPANs), such as wireless light switches with lamps, electrical meters with in-home-displays, consumer electronics equipment via short-range radio that need low data rates. The technology defined by the ZigBee specification is intended to be simpler and less expensive than other WPANs, such as Bluetooth. ZigBee is targeted at radio frequency (RF) applications that require a low data rate, long battery life and secure networking [3], [4], [5].

ONE-NET provides the open design specification necessary to enable a low-cost, low-bandwidth wireless control network. Residential applications need control/automation devices to be low cost, very low power (able to run on batteries), and able to operate in secure wireless communication modes. For the greatest market penetration, these devices must be interoperable, using open design standards. The protocol is small and simple enough to run on a wide variety of low cost microcontrollers [6].

SimpliciTI is a free network protocol stack developed by Texas Instruments. It provides a simple API for communication between radio devices. The protocol is fully supported by the company's devices and they provide sample codes and tutorials. SimpliciTI is suitable for smart metering applications. TI's major design principle was efficient energy use, which makes their devices consume less power [7], [8].

Wavenis Wireless Technology is a wireless connectivity platform dedicated to serve machine-to-machine (M2M) applications. The main requirements in today's data-centric M2M industry are quite different from broadband and high-speed Internet connections, and generally focus on providing ways to transmit small amounts of data wirelessly on a regular but non-permanent basis. Coronis Systems created Wavenis as a proprietary technology in 2001. It was decided to form an open standard based on this technology in 2008. The Wavenis Open Standard Alliance created Wavenis-OSA to manage and govern the technology to evolve [9].

The following technologies were also considered:

Bluetooth is a well-known standard, which has a very limited range and higher energy consumption [10].

Z-Wave is not open source therefore it is not publicly documented. Open-zwave is not ready yet [11].

6LoWPAN is an acronym of IPv6 over Low power Wireless Personal Area Networks. 6LoWPAN is the name of a working group in the Internet area of the IETF. This protocol is not a finished standard yet [12].

DLMS/COSEM: Device Language Message Specification is an abstract modeling tool for communication entities. COmpanion Specification for Energy Metering is a set of rules, based on existing standards, for data exchange with energy meters. Because it covers only the OSI application layer to transport layer, it was not included in this paper [13].

Figure 1 shows a summarized view of the selected solutions and what they implement from the ISO/OSI layer hierarchy.

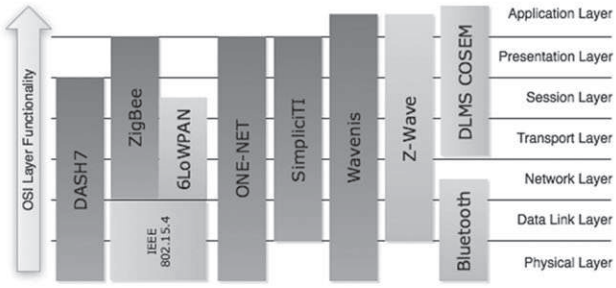

Figure 1 - Investigated technologies and the ISO/OSI layers they cover

4. ANALYZED PARAMETERS

In this section, a uniform system of categorized features is presented to provide a detailed classification of selected solutions.

Features compared are:

Frequency band [MHz]: depending on the frequency used the waves can propagate through water, concrete, urban obstructions with different loss and reflection. E.g. DASH7 uses ISM-band at 433 MHz, in which signals penetrate through concrete constructions, and the frequency is free to use in many countries without much interference. Experiments were also conducted on 868 MHz and found out that 433 MHz has better penetration capabilities and longer range at the expense of lower bit rate. All solutions use ISM frequency bands.

Range [m] means how far two meters can transmit and receive information reliably. DASH7's 433 MHz is applicable for up to 2 kilometers of transmission range outside and about 3 floors indoors with a standard antenna and batteries and regulated transmit power (10 mW in EU).

Measurements were conducted to compare the range of 433 MHz and 868 MHz frequencies. The results are presented in the Section 5.

Table 1 shows a comparison of the investigated systems according to the different features. The Λ parameter in the last row is defined in the following sections.

Feature	DASH7	ZigBee	ONE-NET	SimpliciTI	Wavenis
International standard?	ISO/IEC 18000-7	IEEE 802.15.4	-	-	-
Frequency band [MHz]	433.92	868/915 /2400 (Pro)	US: 915 EU: 866.5	480/868/ 915/955/ 2400	868 (EU) 915 (US) 433 (extension) 2400 (optional)
Indoor range [m]	20-50	10-70	60-100	10-60	200
Outdoor range [m]	1500	1500	500	1739.5 at 433 MHz 825.1 at 915 MHz 314.5 at 2.45 GHz	LOS range up to 1 km 25 mW; LOS range up to 4 km 500 mW
Transmission speed [kbps]	200	20/40/250	38.4-230.4	up to 250	4.8-100 9.6 at 433/868 MHz 19.2 at 915 MHz
Overhead bytes in PHY	20	32	15	14	7
Payload/ packet in PHY [%]	92	76	73	78	97
Latency [ms]	2500-5000 in sleep	15 in sleep	2000 in sleep typically 50	device dependent	12.8-12800 (typ. 12800)
Scalability	15 hops	254 nodes	3 hops	2-~30 nodes (4 hops)	200 nodes
Security	AES, CRC	AES, CRC	XTEA, CRC	XTEA, CRC	AES, RSA, 3DES, FEC with BCH
Technologies used in PHY/MAC	GFSK, CSMA-CA	DSSS, BPSK, CSMA-CA	2-FSK, CSMA	(G)FSK, OOK/ASK	FHSS, GFSK, SCP (Scheduled Channel Polling) similar to SMAC
Λ parameter [bit/J]	5690	2501	1003	1229	5460

Table 1 – Comparison of investigated protocols

5. EFFICIENCY MEASURES

The calculation method presented below grades the smart metering protocols' energy efficiency.

In the presented calculations the devices have the following five distinct modes:

- The device is in sleep mode
- The device transmits user data packets
- The device processes or makes calculations on user data (radio off)
- The device transmits management information
- The device processes management information (radio off)

It is important to distinguish these modes, because the device operates on different energy levels in these different modes. In this approach the user data is handled only in two modes, the management data is considered as overhead.

An interesting and important problem would be to determine whether the data should be processed on the device and transmitted less frequently, or all information should be sent in every case. The formulas below can answer this question.

During the creation of the formulas, relatively easily measurable - or accessible from the data sheets - data is used.

The ratio of user data and all packets sent in time T is calculated in formula (1), where T is the measured time all the calculations are based on.

$$\alpha = \frac{number\ of\ \ user\ data\ packets\ in\ T}{number\ of\ all\ packets\ in\ T} \quad (1)$$

Expression (2) shows the amount of time needed to send data packets in time *T*.

$$t_{data\ send} = \alpha \cdot \frac{|user\ data\ packet|}{transmission\ speed} \quad [\mathrm{s}] \quad (2)$$

, where $|x|$ means the number of bits in x.

The time needed to send management packets in time *T* can be calculated as

$$t_{man\ send} = (1-\alpha) \cdot \frac{|\ management\ packet|}{transmission\ speed} \quad [\mathrm{s}] \quad (3)$$

The following definition gives the amount of time spent by the device in non-sleeping mode.

$$t = t_{data\ send} + t_{data\ proc} + t_{man\ send} + t_{man\ proc} \quad [\mathrm{s}] \quad (4)$$

, where $t_{data\ proc}$ means the time used for processing data packets, and $t_{man\ proc}$ is the processing time of management packages.

E_{sleep} refers to the amount of energy used by the device in sleeping mode.

$$E_{sleep} = (T-t) \cdot P_{sleep} \quad [\mathrm{J}] \quad (5)$$

, where P_{sleep} is the power of the sleeping device. (T-t) is the amount of time spent in sleep mode of time T.

Formula (6) calculates the amount of energy used for sending and processing management packets.

$$E_{management} = t_{man\ send} \cdot P_{send} + t_{man\ proc} \cdot P_{active} \quad [\mathrm{J}] \quad (6)$$

, where P_{send} is the transmitting power consumption (with an active radio module), P_{active} denotes the active mode power consumption (without radio mode on).

Similar to (5) the energy needed to send and process data packets is calculated by formula (7).

$$E_{data} = t_{data\ send} \cdot P_{send} + t_{data\ proc} \cdot P_{active} \quad [\mathrm{J}] \quad (7)$$

, where the power values are the same as before and the time values are labeling the data packets as previously.

With these calculated energy amounts the total energy used by the protocol in time *T* can be summed as

$$E_{total} = E_{sleep} + E_{management} + E_{data} \quad [\mathrm{J}] \quad (8)$$

Assuming also the knowledge of the number of payload bits in data packets, it can be calculated that how much user data the selected protocol can transfer in one energy unit.

$$\Lambda = \frac{|data\ packet\ payload|}{E_{total}} \quad \left[\frac{\mathrm{bit}}{\mathrm{J}}\right] \quad (9)$$

The result of these formulas shows a protocol and device specific number and is suitable for comparison of efficiency of the different solutions. The devices' consumption in different modes is unique and the time they spend in those modes is protocol specific, so this formula combines hardware and software efficiency. The final result is measured in useful bit/Joule ratio, which can be easily used for further calculations of battery lifetime and amount of data transmitted. This result measures the whole system, which consists of a device and a protocol.

Assumptions used in calculations:

- The device is awake in 1% of time and is in sleep mode in 99% of time [14]
- The packets are 20% data and 80% management information filled so $\alpha = 0.2$
- T is one hour

Figure 2 shows the calculated values for each protocol using the same assumptions and MicaZ hardware's performance values [15].

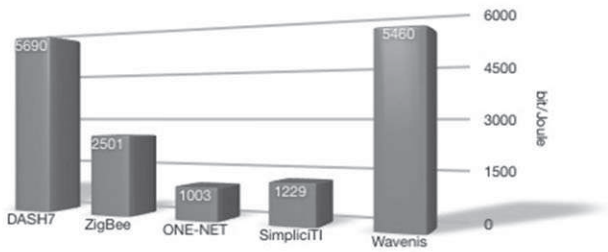

Figure 2 – Λ results compared for investigated protocols

As Figure 2 shows there are significant differences between the solutions. The higher values are better. DASH7 and Wavenis can transmit more user data using 1 Joule of energy. Among all parameters of Table 1, the Payload/packet value correlates the most to Λ.

6. MEASUREMENTS

Another important factor besides energy efficiency - considered in the previous section - is the frequency-dependent range of the various protocols, which means how far the bits containing useful information can be transmitted.

The 2.4 GHz ISM frequency band is crowded, thus jamming and interference is significant. Moreover the waves in this frequency cannot propagate through water and concrete, which can be a disadvantage because of the meters' location, as opposed to the 433 MHz and 868 MHz bands which have suitable properties for smart metering

applications. Therefore, the mesurements were conducted with 433.92 MHz and 868 MHz with 10 mW transmission power in various environments: inside a building, from indoor to outdoor, and LOS environment at an airport. The received signal strengths were recorded.

The first set of measurements was conducted indoors. The results are presented in Table 2 and Figure 3. When the devices were 3 floors away, they lost connection. The building's ferroconcrete structure absorbs radio signals to a great extent, especially at 868 MHz.

Placemark	*433 MHz*	*866 MHz*
A	-14 dBm	-25 dBm
B	-68 dBm	-68 dBm
C	-42 dBm	-61 dBm
D	-86 dBm	-95 dBm
E	-70 dBm	-87 dBm
F	no signal	no signal

Table 3 – Indoor measurements

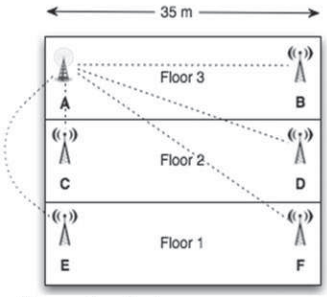

Figure 3 – Indoor measurements

The second set of measurements was conducted from indoor to outdoor. At point C shown on Figure 4 a fracture in signal strength can be noticed, as the measurement was carried out at the opposite side of the building. Table 3 shows the measured values.

Placemark	*Distance from Laboratory*	*433 MHz*	*866 MHz*
A	15 m	-78 dBm	-90 dBm
B	90 m	-80 dBm	-92 dBm
C	100 m	-90 dBm	no signal
D	150 m	-87 dBm	-95 dBm
E	210 m	-84 dBm	-94 dBm
F	250 m	-87 dBm	-94 dBm

Table 3 – Indoor to outdoor measurements

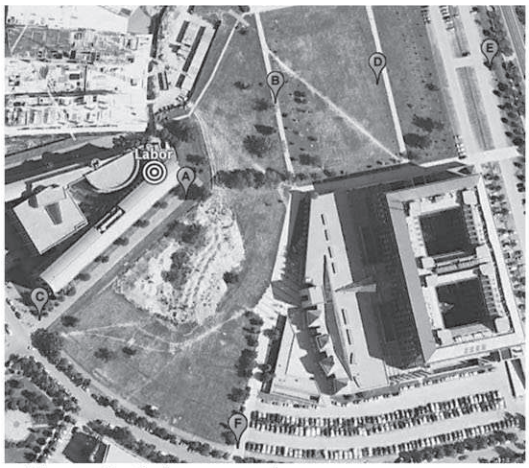

Figure 4 – Indoor to outdoor measurements map

The third set of measurements was conducted outdoors at an airport. Figure 5 shows a map of the location. Table 4 concludes the measured values alongside the calculated values for 433 MHz, 868 MHz and 2.4 GHz. The calculated values estimate the ideal Signal to Noise Ratio (SNR) of a clear channel. The measured values are lower than the calculated values, as background noise was significant.

Place-mark	*Distance to Base*	*433 MHz measured*	*433 MHz calculated*	*868 MHz calculated*	*2.4 GHz calculated*
A	173 m	-70 dBm	-58.65 dBm	-64.68 dBm	-73.51 dBm
B	335 m	-79 dBm	-64.39 dBm	-70.42 dBm	-79.25 dBm
C	564 m	-85 dBm	-68.92 dBm	-74.95 dBm	-83.78 dBm
D	774 m	-95 dBm	-71.67 dBm	-77.69 dBm	-86.53 dBm
E	1045 m	-100 dBm	-74.28 dBm	-80.3 dBm	-89.14 dBm

Table 4 – Outdoor measurements

Figure 5 – Outdoor measurements map

The fourth set of measurements was conducted on 433 MHz in a rural environment. These measurements were based on a real-world scenario as the meter was placed in a chamber (at the water pipes) and at the electricity box. The measurement points are presented on Figure 6. The measured values for the two scenarios are summarized in Table 5. The water chamber significantly shades the signal, so at further distances no signal was measured. The signal strength dropped more rapidly than at the second measurement, where indoor to outdoor performance was evaluated.

Placemark	*Distance from meter*	*Water chamber*	*Electricity meter*
A	192 m	-101 dBm	-85 dBm
B	149 m	-99 dBm	-83 dBm
C	77 m	-95 dBm	-73 dBm
D	19 m	-75 dBm	-54 dBm
E	79 m	-93 dBm	-78 dBm
F	107 m	-100 dBm	-91 dBm
G	195 m	no signal	-94 dBm
H	266 m	no signal	-98 dBm
I	305 m	no signal	-97 dBm
J	354 m	no signal	no signal
K	336 m	no signal	-100 dBm
L	289 m	no signal	-96 dBm
M	316 m	no signal	-96 dBm

Table 5 – Rural environment measurements

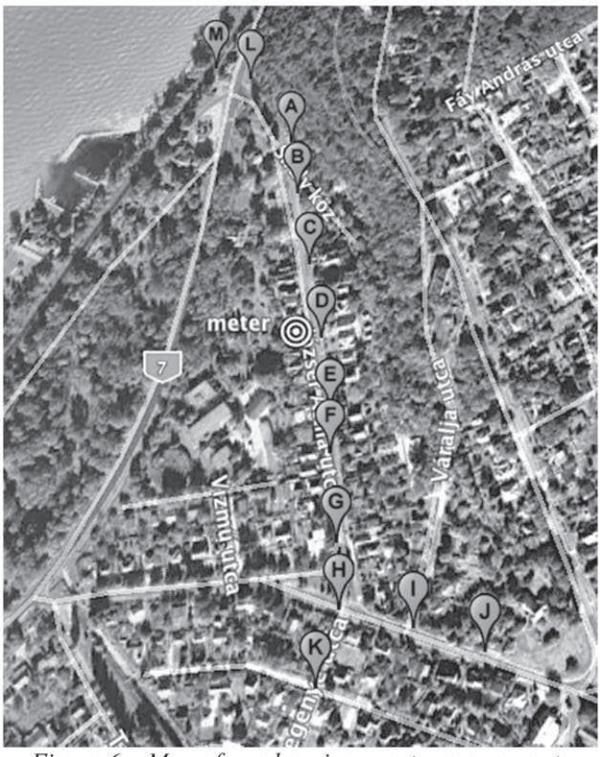

Figure 6 – Map of rural environment measurements

The measurements proved that a 433 MHz frequency signal has better propagation properties, than an 868 MHz signal, hence more suitable for smart metering applications.

7. CONCLUSIONS

In this article different wireless smart metering technologies were investigated and a formula was created which enables to determine the efficiency of the protocols in bit/Joule. The efficiency of wireless smart metering technologies were calculated. According to the results, DASH7 and Wavenis has the best bit/Joule ratio. Also the range of used frequencies were compared.

This research helps companies to decide which technology to select according to their goals. A formula can be constructed to give a preference-weighted correlated evaluation about the strengths and weaknesses of each protocol according to their custom needs.

Further research can be conducted to determine the impact of processing and storage of data on the devices, instead of instantaneous transmission.

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