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An analysis of energy efficiency in Wireless Sensor Networks (WSNs) applied in smart agriculture

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ABSTRACT

In this paper the usage of Wireless Sensor Networks (WSN) in smart agriculture applications was analyzed. The main focus of the paper is on the power consumption of the various WSN components, on the both levels, physical and functional. The analysis, from the energy efficiency aspect, includes a comparative review and discussion of the most commonly used protocols on the physical, data link and network layers. The analysis outcome provides a precise identification of the main power consumers, the magnitude of their consumption, and a deep understanding of the key mechanisms that should be applied in order to improve the energy efficiency in a WSN. The analysis also includes simulation of a WSN operation in a smart agriculture application. The simulation scenario and the measured values of the average power consumption and the average time of activity of the radio component of each network node provide a confirmation of the key points of the previously performed analysis and detailed insights into the possible directions of the strategy for energy efficiency improvement. Additionally, the simulation results reveal the magnitude of the energy savings that can be accomplished by deploying the duty cycle mechanisms within the WSNs. Finally, the paper includes a discussion about various factors and the way they impact the level of energy efficiency, which have to be addressed within the requirements gathering, comprehensive analysis and the design phases of a WSN life cycle implementation.

1. Introduction

Since the great potential of IoT (Internet of things) in all aspects of the modern life has been widely recognized, sensors, wireless networks and software applications have become an important and valuable asset of modern agricultural infrastructure. Based on collected data, powerful analytical tools are able to provide information about optimal agrotechnical measures necessary for ensuring optimal conditions of production and quality. Such an analysis of data, combined with inputs from other sources, can anticipate any danger that may occur, provide various insights and answers on what happened as well as recommendations on actions to be undertaken.

In this paper, we provide a broader integrated view on energy consumption mechanisms in WSNs (Wireless Sensor Networks). We believe, it is beneficial for researchers and all those who are interested in practical implementation of WSNs, to know the major challenges and potential options in pursuit of energy efficiency improvement. Moreover, we cover the recent progress and provide an overview of the main communication stack protocols, primarily from energy efficiency perspective. Though, other network performance aspects as delay, overhead, throughput etc. are also taken into consideration. Contribution of this paper can be summarized as follows:

(i) A detailed overview of the energy consumption in a WSN, along with identification of the main energy consumers on the both physical and functional level of a sensor node.
(ii) A discussion and comparison of technical details of the widely used energy saving mechanisms built into the various protocols across the communication stack layers of a WSN.
(iii) A simulation of the WSN operation by using the Cooja simulator, with a detailed analysis of the average power consumption and the average duty cycle for all the network nodes.
(iv) An analysis of some additional elements important for design and implementation of an energy efficient WSN in smart agriculture applications.

The rest of this paper is organized as follows: In Section 2 is presented architecture of a typical sensor node and an appropriate power consumption analysis. In Section 3, a discussion and comparative analysis of the media access protocols in terms of the energy efficiency is provided. In Section 4, a detailed comparative analysis of the energy efficient routing protocols is presented. Section 5 contains simulation of

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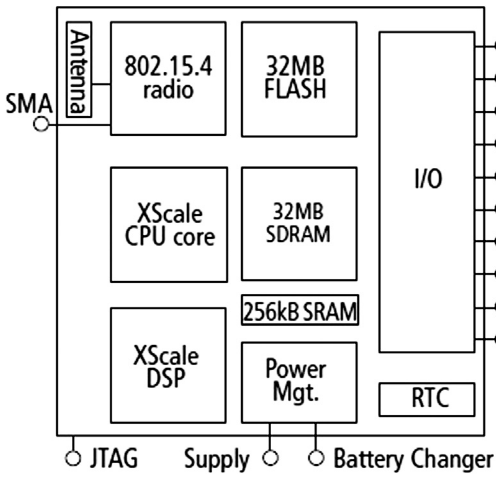


Fig. 1. Blok diagram of a high-performance WSN node Imote2.

a WSN operation in a smart agriculture application and discussion of the simulation outcomes from the energy efficiency point of view. Section 6 contains a discussion about some additional factors and their impact on design of an energy efficient WSN in a smart agriculture context. Section 7, summarizes the conclusions.

2. Sensor nodes

Sensor nodes represent the sensing layer of a WSN. They typically continuously sense targeted physical parameters in a real-time manner. In the same way, they monitor working status and location of the equipment. As a result of sensing, sensor nodes periodically, or upon certain predefined events, generate information in the form of electrical signals. These signals are further processed and prepared for wireless transmission through the network to the sink node or base station, which is a central processing and controlling unit in a WSN. What is an event definition and how frequently readings of the monitored parameters are taken depends on the specific requirements of each agriculture application. Clearly, it is managed by application layer a WSN.

In a practical realization, such as the one depicted in Fig. 1, a typical sensor node consists of a board that includes microcontroller, radio transceiver with antenna for communication with neighboring nodes, power supply, interfaces for programming and debugging, internal memory as well as external flash memory for storing sensor readings. On top of this, it includes a variety of typical sensors which are sometimes built in a separate module called sensor module. Some of them are used in agriculture applications, as such are sensors for air temperature and humidity, soil moisture, leaf wetness, atmospheric pressure, solar radiation, dendrometers, the soil temperature etc. Most of the sensor nodes run their own operating system developed for small form-factor, low-power embedded devices, such as for example TinyOS, Contiki, etc. They provide inter-processor communication with the radio and other components in the system, control power consumption, control attached sensor devices, and provide support for network messaging and other protocol functions (Selmic and Phoha, 2016).

Each of these logical and physical components needs energy to operate. Sensor nodes are typically powered by batteries with a limited lifetime and despite the fact that in the most cases the batteries are rechargeable, the problem of energy consumption in WSNs stays high on the researcher's open topics agenda. Basically, the essence of problem with batteries lies in their lifetime and its potential impact on the both node's and the entire WSN lifetime. Namely, by definition a sensor node's lifetime is defined as the node's operating time without the need for any external intervention, like battery replacement. A WSN lifetime can be defined as the lifetime of the shortest living critical node in the network (Nandini Mukherjee, 2016). However, depending on the network design, i.e. its resilience and robustness, as well as concrete agriculture application features, it can be defined as the lifetime of sink or some other main node in a WSN, which is – as already mentioned – in direct correlation with the batteries lifetime. Another potential problem is related to impact of batteries lifetime on node's performance. Namely, when going toward the end of the battery lifetime, the nodes start degrading their performances, but do not necessarily stop working. They can support only some of their build-in functionalities (the radio can send, but not receive) or deliver faulty results – the sensors.

Therefore, efficient power management in the sensor nodes is a critical factor for the network's lifetime. In order to prolong a WSN lifetime, it is of crucial importance to reduce the energy consumption of the nodes as much as possible. How much energy a sensor node would need when running in a certain period of time depends mainly on the functionalities embedded in it. As reported in Forster (2016), the most power consuming ones are RF transceiver and flash memory components. Based on experimental results, a similar conclusion is reported in (Raghunathan et al., 2002). Moreover, the experimental results have shown that local computation or data processing consumes significantly less energy, the order being one thousandth of that required for transmitting single bit of data (Raghunathan et al., 2002); (Nandini Mukherjee, 2016). As an illustration, in Table 1 is given the nominal power consumption of a Tmote Sky sensor node (advanticsys.com). Though, the energy consumption of the sensing subsystems may be generally considered to be negligible, compared to other sensor node components, some particular types may end up requiring more energy. This could be the case, for example, with sensing modules that contains the atmospheric pressure sensor MPX4115A. Namely, due to its relatively large consumption compared to the other sensors, there is a recommendation this sensor to be powered independent from the other sensors on the Agriculture 2.0 Board (libelium.com).

3. MAC protocols in WSN

3.1. The principles of energy efficiency in MAC protocols

As already said, a major power consuming component of a sensor node is the radio. On the other hand, the radio is controlled by a MAC (Medium Access Control) protocol. Therefore, an efficient MAC protocol might increases the lifetime of a sensor network to a great extent and vice versa. In addition, the MAC protocol controls how the nodes share the wireless medium. Looking at the Table 1, it could be noted that sleep mode of a sensor node, as expected, is the least power consuming mode. This fact defines one of the three key criteria for designing a good Media Access Protocol (MAC):

(i) maximize the throughput,
(ii) minimize delay and
(iii) save the energy. Additionally, in the case of WSNs, it needs to be able to switch off devices so nodes do not waste any valuable energy.

On the other hand, there is another interesting fact, although not so intuitive and obvious. Namely, it says that node spends more energy listening the channel than while sending (Forster, 2016; Chand, 2015).

Table 1
Nominal power consumption of Tmote Sky nodes.

Microcontroller unit	Radio	Current draw
MCU on	RX	21.8 mA
MCU on	TX	19.5 mA
MCU on	Radio off (sleep)	1.8 mA
MCU idle	Radio off	54.5 μA
MCU	–	5.1 μA

Therefore, the time that node spends in listening mode needs to be minimized as much as possible. This is the fourth main design criteria for energy efficient medium access protocols. The above mentioned four criteria can be also expressed through the following four goals:

(i) minimize collision,
(ii) minimize overhearing,
(iii) minimize idle listening and
(iv) minimize overhead.

Clearly, it is not realistic to expect that any solution could meet all four criteria to the same great extent. Some trade of is inevitable. However, the energy saving aspect of each of these four goals is significant and it is something we will briefly elaborate and discuss here:

- The collision avoidance is supposed to work by shutting down the nodes around the sender and receiver. By minimizing collision the MAC protocol avoids resending packets, which saves the energy that would be spent on resending the packets.
- By minimizing overhearing, a MAC protocol saves the energy in a way that minimizes the number of packets received by the nodes which are not the ultimate destination of these packages. Namely, these packets cause additional energy consumption by keeping the nodes in the receive instead of the sleep mode. The standard approach is adding a header with the destination address.
- The idle listening refers to the mode when a node is just listening and nothing happens. Since the energy consumption is about the same in the listening and receive mode, it is clear that such a mode need to be minimized as much as possible.
- The overhead refers to transmitted bits not carrying any user useful information. These bits are so called redundant bits, embedded in packets. Since for each bit when sent or received some valuable energy is spent, it is clear that this kind of energy spent need to be minimized.

3.2. The energy saving mechanisms in MAC protocols and its deployment in smart agriculture

One of the simplest, yet efficient MAC protocols is Time Division Multiple Access (TDMA) protocol (Forster, 2016). It operates in the way that time is divided into rounds and rounds are divided into slots. Each node is then given sending control over one slot. The number of slots depends on the number of nodes in the network. The length of one slot and thus the length of a round depend on the technology used and on the expected length of the packets. In Nesa Sudha et al. (2011), a TDMA based MAC protocol was used to collect environmental data such as soil moisture and temperature of an irrigation system. In Raju Bhowmik and Ajita Pathak are presented simulation results of an energy efficient WSN with a TDMA based MAC protocol used for the greenhouse temperature monitoring. Equally simple, yet more efficient and powerful is Carrier Sense Media Access (CSMA) MAC protocol. Sender first listens on the shared channel and if it is free, it tries to send. Since the primary source of energy waste in these protocols is idle listening, in order to greatly save energy, so called duty cycling is widely adopted in WSNs. More precisely, it became a fundamental mechanism of the CSMA class of MAC protocols. In this technique, each node alternates between active and sleep states. Two nodes can communicate only when they are both active. In synchronous MAC protocols, neighboring nodes are synchronized to wake up at the same time. Therefore, the communication is facilitated and the focus is on the delay reduction and throughput improvement. Asynchronous MAC protocols, on the other hand, focus on how to efficiently establish communication between two nodes that have different active/sleep schedules (Huang et al.). Some of the most known duty cycling MAC protocols of this class are Sensor-MAC (S-MAC), Timeout-MAC (T-MAC) and Berkeley-MAC (B-MAC) also known as Low Power Listening (LPL). In (López et al., 2011) is proposed a WSN for monitoring horticultural crops that are distributed among small plots scattered at distances of up to 10 km from one another. The technology used for the practical implementation of the architecture is based on the B-MAC protocol for assuring a high degree of sensor node power autonomy. Nowadays, BoX-MAC (Moss and Levis, 2008) is considered the de-facto standard, although A-MAC (Dutta et al., 2010) is considered the best algorithm ever. BoX-MAC is not as complex as A-MAC. It is simple to understand and use, as well as it is already embedded in the most of the WSN operating systems. When it comes to the hardware level, IEEE 802.15.4 (IEEE, 2014) is a technical standard which defines the operation of Low-Rate Wireless Personal Area Networks (LR-WPANs) – part of the ZigBee standard. However, it does not offer any energy saving or sleeping options. ZigBee is a protocol stack with embedded CSMA collision avoidance (CSMA/CA) protocol. It is widely used in practical implementations of the low-power, low data rate, and close proximity WSNs in the agriculture applications. An application in cultivating the potato crop by using a WSN based on the CSMA/CA is studied in (Sherine, 2013). In (Sahota et al., 2011) is proposed a new MAC protocol for which authors have reported improvement of 65% in energy efficiency compared to S-MAC protocol for the same level of throughput.

4. Energy efficient routing protocols in WSNs

4.1. The main requirements

A routing protocol is an algorithm, which defines how exactly to route a packet from the source node to the destination. It uses one or more metrics, such as geographic location, number of hops, delivery delay etc. to evaluate the network conditions and to decide what to do. The main WSN routing protocol requirements are:

- Energy efficiency: A routing protocol need to be able to cope with node sleep and to have as little as possible discovery and route management related overhead.
- Flexibility: A protocol must be able to cope with nodes entering or exiting the network (e.g., dead nodes or new nodes) and with changing link conditions (Forster, 2016).

Routing highly depends on the MAC and link layer protocols. It is very sensitive to link quality – the more stable links are, the better the routing protocol works.

4.2. Geographic energy-aware routing protocols

There are a couple of routing schemes based on geographic locations that are energy-aware and attempt to conserve energy. Geographic Adaptive Fidelity (GAF) routing is one of them. It combines the concepts of geographic location-based routing and hierarchical routing. GAF is able to substantially increase network lifetime (Xu et al., 2001). Geographic and energy aware routing (GEAR) uses an energy-aware metric in estimating the cost function to balance energy consumption that leads to an energy-efficient network (Yu et al., 2001). The wireless sensor network employing Hierarchical power-aware routing (HPAR) (Li et al., 2001) is assumed to be divided into zones that comprise sensor nodes in geographic proximity. Each zone decides on the hierarchical routing used for its data across other zones. The routing path is chosen in the way that total remaining power of all the nodes in the path is the maximum over all minimum of the remaining power. This path is called the max–min path. Another algorithm proposed in Li et al. (2001), the zone-based routing, finds a global path across zones based upon the max–min zPmin algorithm. Zone level power estimates are used for routing a message. A global controller manages the zones. Zone-based routing is able to drastically reduce the running time to find a route. Also within each zone the local routing path is computed in such a way that it does not decrease the overall power level of the zone.

4.3. Clustering based energy efficient routing protocols

The work in (Pramanik et al., 2014) presents an analysis and comparison of a number of energy-efficient routing protocols. Low Energy Adaptive Clustering Hierarchy (LEACH) is a routing protocol in which not all sensor nodes have to send data to the base station or the sink. This saves power consumption since data from sensor nodes are sent only to respective cluster-heads. Thus, cluster-heads consume more energy than other nodes. Hence, the role of a cluster-head is rotated among the nodes in a cluster. The feature of selecting cluster-heads and reselecting them at regular intervals saves energy. Another important feature adopted by a non-cluster-head node is sending data only during its scheduled transmission slot and then turning its radio off – going into sleep mode. All these features help conserve energy and increase network lifetime. The PEGASIS, power-efficient gathering in sensor information systems (Lindsey and Raghavendra, 2002), is a near-optimal protocol. Though PEGASIS does not have any clustering overhead, it has to manage topology dynamically. This is because a sensor node must know the energy status of its neighbors and route its data accordingly. However, PEGASIS scores over LEACH in the way that it eliminates dynamic cluster formation, limits transmissions to the base station, and introduces data aggregation. The PEGASIS distributes energy load among the nodes and thus increase the lifetime and quality of the network. The TEEN (threshold-sensitive energy-efficient sensor network) protocol has certain features in common with LEACH, for example, rotation of cluster-heads. Energy conservation results from clustering. The setting of different threshold levels in TEEN also saves power because the transmission of data depends on threshold levels. The APTEEN (adaptive periodic threshold-sensitive energy-efficient sensor network) protocol is an improvement over TEEN. Both APTEEN and LEACH follow TDMA schedules and hence their radios are turned off when not in use and this also saves energy. Simulation experiments of TEEN and APTEEN show that both outperform LEACH. TEEN, however, gives best performance among these three. The APTEEN performance level is somewhere between those of LEACH and TEEN with respect to energy dissipation and network lifetime (Nandini Mukherjee, 2016). There are many routing techniques that are designed with the aim of optimizing or even minimizing energy consumption of the sensor nodes. A protocol called Equalized Cluster Head Election Routing Protocol (ECHERP), which pursues energy conservation through balanced clustering, is proposed in (Nikolidakis et al., 2013). Capitalizing on it, a scheme based on the collaboration of an integrated system for automated irrigation management has been proposed in (Nikolidakis et al., 2015). It models the network as a linear system and, using the Gaussian elimination algorithm, calculates the combinations of nodes that can be chosen as cluster heads in order to extend the network lifetime.

4.4. Routing protocols exploiting data aggregation

In smart agriculture and environment monitoring applications sensing data from neighboring nodes are usually spatially correlated (Gao et al., 2010). Therefore, data aggregation has been naturally considered as an essential tool to integrate such data to reduce redundancy and minimize the number of transmissions, resulting in lowered energy consumption (Krishnamachari et al., 2002). There are studies that combine data aggregation with other techniques to save energy, e.g. with cluster-based routing (Heinzelman et al., Oct. 2002), channel assignment (Yen and Lin, 2009) and power scheduling (Eun et al., Sept. 2006). Virtual grid architecture (VGA) routing (Al-Karaki et al., 2004) builds clusters. Each cluster has a cluster head and data aggregation is performed at the both local (cluster) and global level. It uses a various algorithms for optimal selection of the local and global aggregation points. Some of them maximizing network lifetime are integer linear programming (ILP), genetics algorithm-based heuristics, k-means heuristic, greedy heuristic and clustering-based aggregation heuristic (CBAH) (Al-Karaki and Kamal, 2004). Simulation results show that CBAH outperforms LEACH and PEGASIS with respect to network lifetime. At the same time, it also achieves acceptable latency without sacrificing quality (Nandini Mukherjee, 2016).

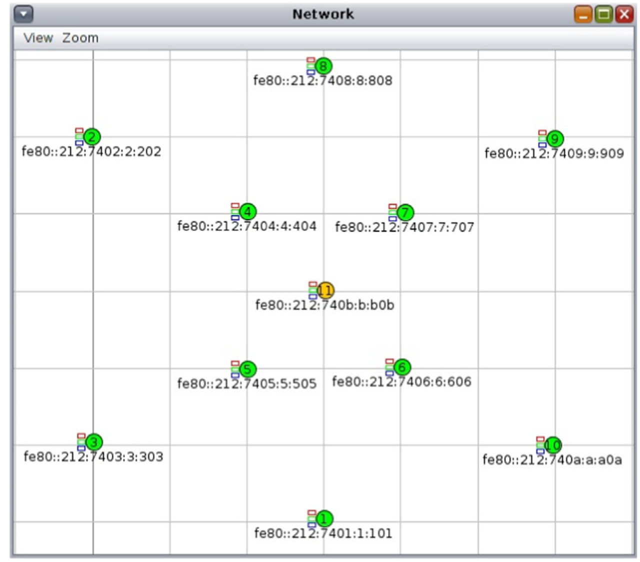


Fig. 2. The diagram of the simulated network with 10 m background greed.

5. The simulation

In order to illustrate the significance of the duty cycle mechanism in WSNs, from the energy saving perspective, we have simulated a WSN operation by using the Contiki's Cooja simulator, which is one of the most popular open source platforms used for WSN simulations. The simulated WSN consists of 11 Tmote Sky's CC2420 ultra low power IEEE 802.15.4 compliant wireless sensor modules and operates in a strong multipath fading channel environment. The network diagram including the arrangement of the nodes and 10 m background greed is shown in Fig. 2. As a routing protocol is used the RPL (IPv6 based Routing Protocol for Low power and Lossy Networks). The air temperature sensors of the green colored nodes are continuously sensing and sending the information to the yellow colored sink node, positioned in the center of the covered area. It is assumed that the sink node is powered by an ideal power source delivering a constant voltage of 3 V and an unlimited amount of current. Within the simulation scenario, we have measured the average energy consumption and the radio activity duty cycle periods of the sensor nodes during the network simulation runtime. Moreover, we have run the simulation for two popular asynchronous MAC protocols available in ContikiOS that aim at energy saving, CX-MAC and ContikiMAC, and compared their results, whereas all the other elements of the network and operating conditions remain identical.

As it could be seen in the Fig. 3, in the case of the ContikiMAC protocol, the average radio duty cycle per node is around 0.9%, which results in a tremendous energy saving, while in the case of the CX-MAC protocol it is around 6%. Therefore, from the energy saving perspective, we could say that the ContikiMAC protocol provides better results than the CX-MAC protocol. Though, it is important to highlight that in the case of no duty cycle mechanism implemented, as we have discussed in the Section 3, the active period of the sensor nodes would be around 100%, which means that their radio components would be permanently on during the network runtime, which would result in a huge waste of the energy.

Consequently, it is obvious, as depicted in the Fig. 4, that the measured average power consumption per node during the simulation runtime is much lower in the case of the ContikiMAC protocol. A more

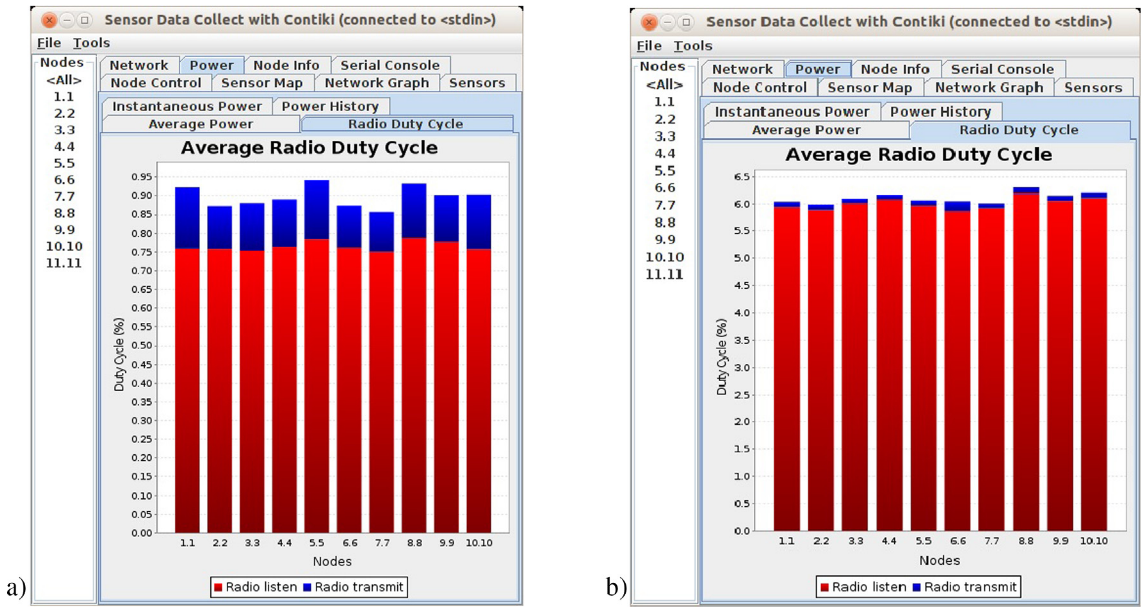


Fig. 3. The average radio duty cycle per node during the simulation runtime: (a) ContikiMAC protocol, (b) CX-MAC protocol.

detailed view of the measured values during the simulation runtime is given in the Figs. 5 and 6.

6. Discussion

A block diagram of a WSN implementation life cycle is provided in the Fig. 7. The focus of this paper is on the first three phases, i.e. the environment input and requirements, analysis and planning, and design phases. We are not going to discuss the rest of the implementation life cycle phases, since they are predominantly subjects of the project management and related methodologies. Moreover, the project management tools that facilitate project development and implementation are usually available within an integrated development environment that comes with the wireless microcontroller modules. On the other hand, the construction phase is realized by usage of the wireless microcontroller modules compliant with a number of wireless communication standards and protocols. These modules are highly configurable, with default settings providing the compliance with the radio standards and various protocols. The integrated development environment and tools allows further customization according to the specific needs of the smart agriculture application by an available and extensive line of development tools, including tools to evaluate the performance of the processors, generate code, develop algorithm implementations, fully integrate and debug software and hardware modules etc.

Since our focus is on the first three phases, next to each of them are highlighted details that should be carefully analyzed within that particular phase. Thus, next to the block representing the environment input and requirements phase are listed some of the key inputs and environment related details that need to be included into the requirements document. Then, next to the block representing the analysis and planning phase are listed factors which must be thoroughly analyzed and objectively estimated. Output of this phase is crucial for making the right choices on important topics concerning the network design.

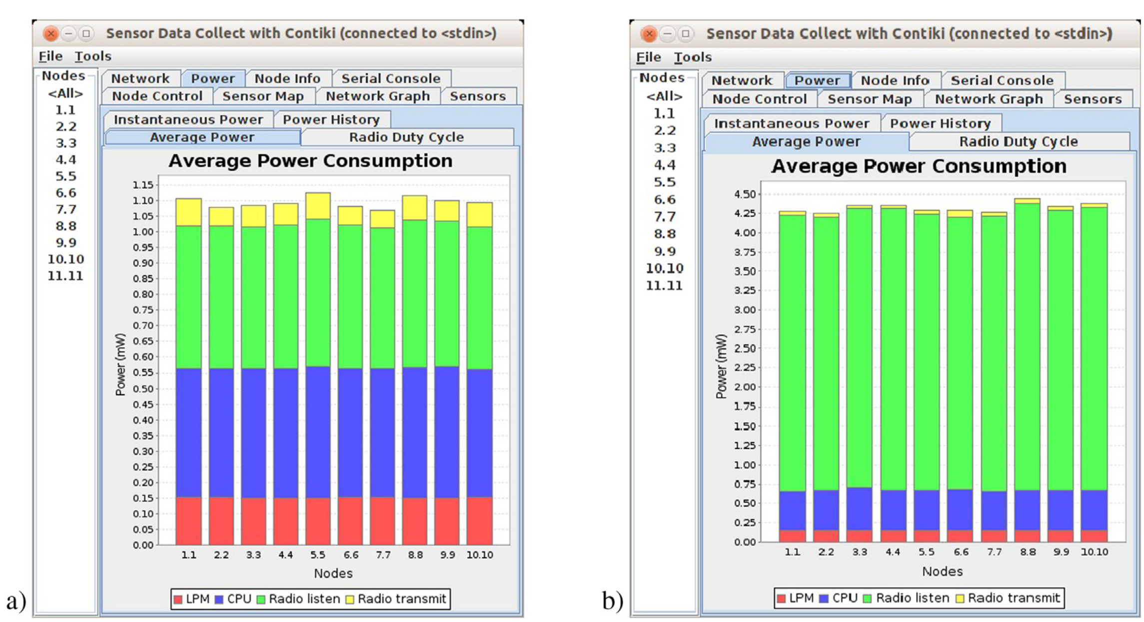
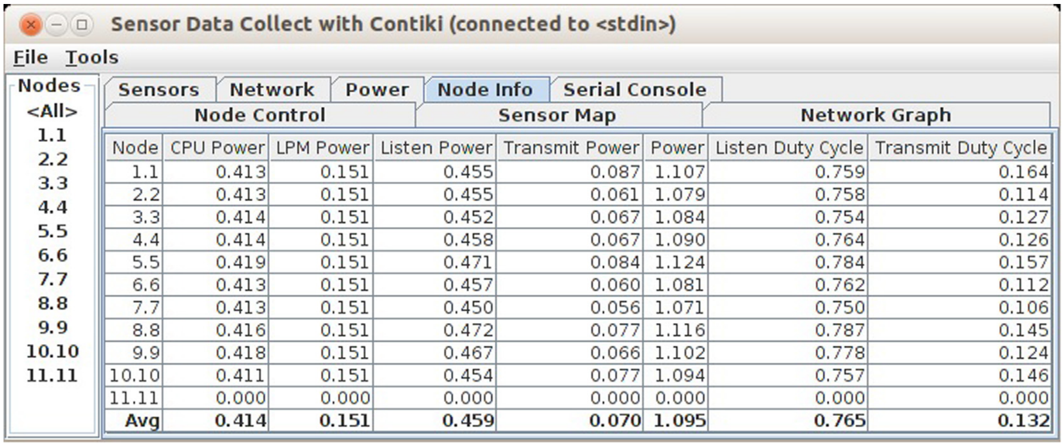
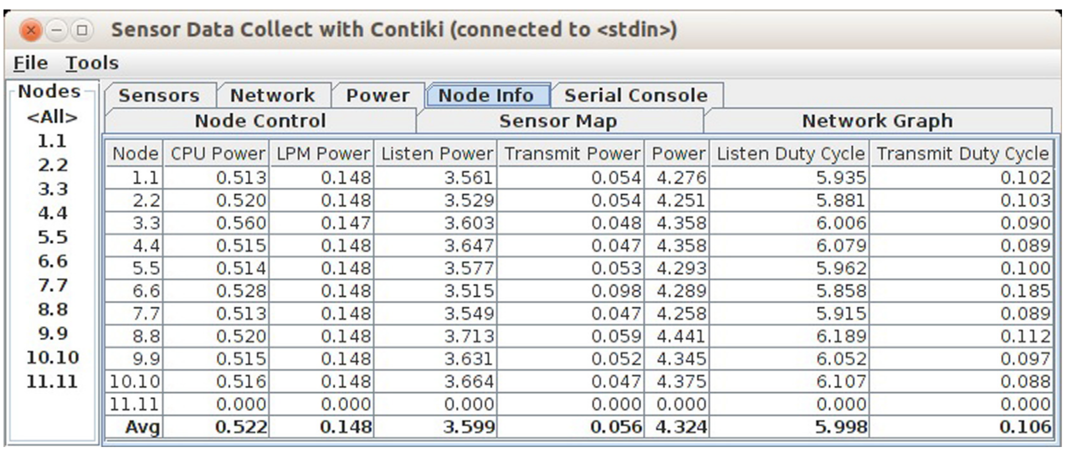


Fig 4. The average power consumption per node during the simulation runtime: (a) ContikiMAC protocol, (b) CX-MAC protocol.



Node	CPU Power	LPM Power	Listen Power	Transmit Power	Power	Listen Duty Cycle	Transmit Duty Cycle
1.1	0.413	0.151	0.455	0.087	1.107	0.759	0.164
2.2	0.413	0.151	0.455	0.061	1.079	0.758	0.114
3.3	0.414	0.151	0.452	0.067	1.084	0.754	0.127
4.4	0.414	0.151	0.458	0.067	1.090	0.764	0.126
5.5	0.419	0.151	0.471	0.084	1.124	0.784	0.157
6.6	0.413	0.151	0.457	0.060	1.081	0.762	0.112
7.7	0.413	0.151	0.450	0.056	1.071	0.750	0.106
8.8	0.416	0.151	0.472	0.077	1.116	0.787	0.145
9.9	0.418	0.151	0.467	0.066	1.102	0.778	0.124
10.10	0.411	0.151	0.454	0.077	1.094	0.757	0.146
11.11	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Avg	**0.414**	**0.151**	**0.459**	**0.070**	**1.095**	**0.765**	**0.132**

Fig. 5. A detailed view of the average power consumption and radio duty cycle values recorded during the simulation for the ContikiMAC protocol applied.



Node	CPU Power	LPM Power	Listen Power	Transmit Power	Power	Listen Duty Cycle	Transmit Duty Cycle
1.1	0.513	0.148	3.561	0.054	4.276	5.935	0.102
2.2	0.520	0.148	3.529	0.054	4.251	5.881	0.103
3.3	0.560	0.147	3.603	0.048	4.358	6.006	0.090
4.4	0.515	0.148	3.647	0.047	4.358	6.079	0.089
5.5	0.514	0.148	3.577	0.053	4.293	5.962	0.100
6.6	0.528	0.148	3.515	0.098	4.289	5.858	0.185
7.7	0.513	0.148	3.549	0.047	4.258	5.915	0.089
8.8	0.520	0.148	3.713	0.059	4.441	6.189	0.112
9.9	0.515	0.148	3.631	0.052	4.345	6.052	0.097
10.10	0.516	0.148	3.664	0.047	4.375	6.107	0.088
11.11	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Avg	**0.522**	**0.148**	**3.599**	**0.056**	**4.324**	**5.998**	**0.106**

Fig. 6. A detailed view of the average power consumption and radio duty cycle values recorded during the simulation for the CX-MAC protocol applied.

Hence, the most interesting is the design phase, where actually all features and attributes of the future WSN are determined, such as the Radio frequency (RF) range, network topology, network clustering, node density, power distribution across nodes, applied medium access and routing protocols, error controlling schemes, modulation and demodulation schemes, encoding and decoding methods etc.

Apart from the protocols and mechanisms we have discussed within the previous sections of this paper, as stated above, in the rest of this section we are going to discuss some additional elements impacting design of the energy efficient WSN in the smart agriculture applications. Although, the most of these elements have a multiple impact on the solution design, we will focus on those impacts that are more significant.

The environment characteristics of the agriculture fields might significantly shape the multipath fading channel model, which consequently impacts the link reliability. The Bit Error Rate (BER) is a good indicator of the link reliability. It is directly proportional to the both received signal-to-noise ratio (SNR) ($Es/N0$) and the output transmitter power level *Pout*. Therefore, a reliable data communication in WSN can be provided either by increasing the output transmit power (*Pout*) or by using a suitable error control scheme. Since a sensor node has limited power resources an optimal error control strategy has to be applied in the WSN. In general, there are two types of such schemes: Forward Error Correction (FEC) and Automatic Repeat Request (ARQ). The usefulness of ARQ schemes in multi-hop sensor networks is limited due to additional retransmission energy cost and overhead. On the other hand, additional processing power that goes into encoding and decoding in FEC schemes is something that must be taken into account. In Nandi (2011), based on the simulation results it is observed that WSN energy efficiency degrades and the energy requirement increases significantly in presence of Rayleigh fading. Clearly, this observation is valid in general, i.e. for all types of the fading channels. The simulation results have also revealed that FEC schemes provide higher energy efficiency compared to ARQ schemes under same network conditions and packet size. Moreover, it is observed that required energy in FEC schemes decreases with increase in the packet length, while in ARQ schemes required energy increases with increase in the packet length.

In accordance with all the above stated, another option in improving the link reliability, i.e. reducing the BER, might be shortening the distance between the nodes. Namely, a targeted SNR could be achieved either by increasing the output transmitter power for a given distance between the nodes or vice versa, by shortening the distance between the nodes for the same given output transmitter power. This option and error control scheme are mutually complementary and might be applied together. Shortening the distance between the network nodes impacts the node density in a WSN, i.e. the total number of nodes for a given size of the area to be covered. An example of calculating the number of sensor nodes required for precise potato farming, for a given size, shape and environment characteristics of the field is given in (Sherine, 2013).

Another important topic impacting WSN design, closely connected with the previous one, is moving of the sensor nodes. Namely, it has been proven in the theory of wireless communications that moving nodes are exposed to an enhanced fading severity which is positively correlated with the velocity of the nodes.

The network topology is also to a certain extent conditioned by the

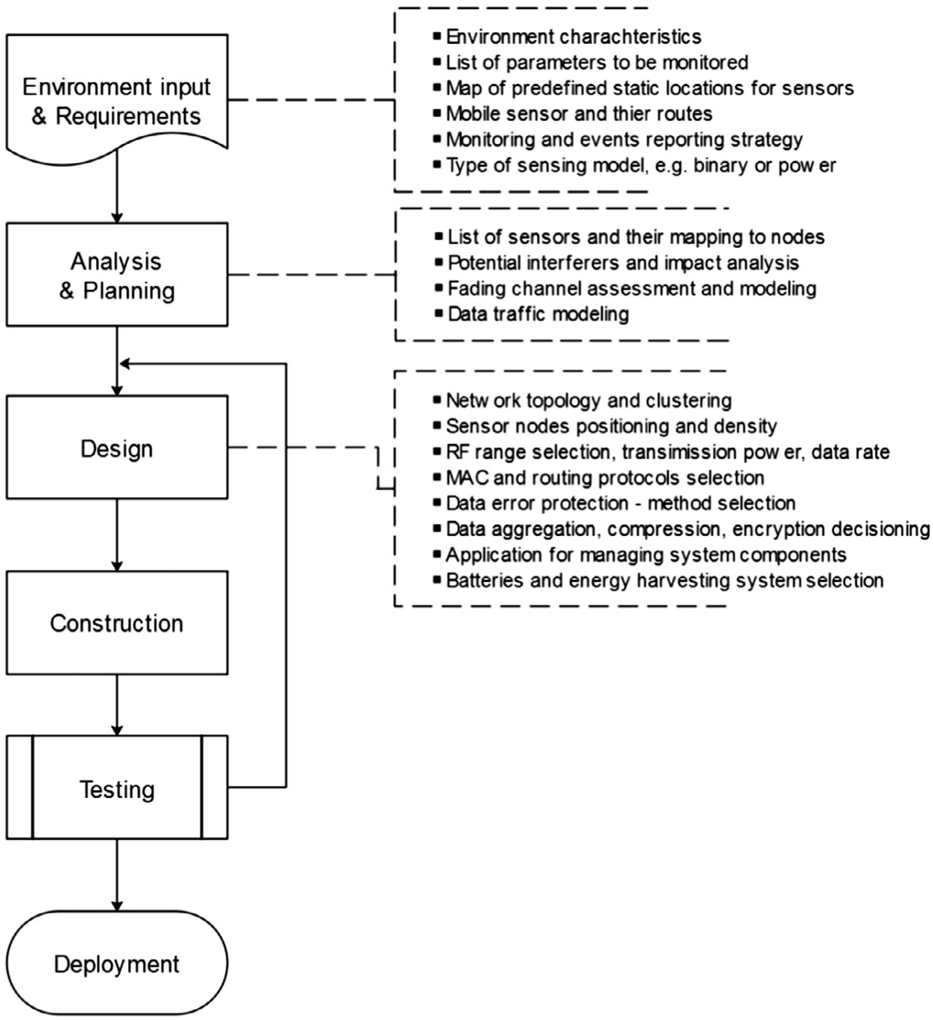


Fig. 7. A block diagram of the WSN implementation life cycle.

above discussed environment characteristics, and a number of other factors such as locations and number of the sensor, the RF module range, the type of the information sent to the base station, estimated volume of the traffic etc. There are three main types of network topology: star, mesh and star-mesh hybrid topology. The star topology takes advantage of the low power consumption. The advantage of the mesh topology is that if a sensor node fails, communication is possible via other nodes that are within the communication range, while the major disadvantage is that this topology uses more power due to redundant data transmission. The star-mesh topology combines the advantages of the both types. As a rule, nodes at the edge of the network are usually low-energy nodes, while nodes at the heart of the mesh have higher power since they typically forward messages between large numbers of nodes and serve as gateway nodes. In some cases it is recommended to organize nodes of the WSN in clusters. That could be the case of a large area, with large number of sensor nodes, especially when the area consists of several scattered parcels. In such cases, the sensor nodes would be organized into clusters and a clustering algorithm is needed to address the energy efficiency and load balancing of the WSN. Some of them we have discussed in Section 4.

Within the analysis phase, it should be also investigated are there in a relatively close proximity, e.g. on the neighboring parcels, already deployed WSNs. This is important due to possible interferences that might come from the neighboring WSNs. The interferences would further increase BER, cause higher power consumption of the nodes, and therefore additionally degrade the WSN energy efficiency. Along with worsened energy efficiency, the interferences negatively impact other network parameters important for its normal operation, such as delay, throughput etc. This information is valuable when deciding on many parameters, such as transmission band, i.e. the frequency range to be used for the signal transmission, distribution of the transmission power per nodes, the network node density, selection of the FEC scheme etc. The similar conclusions are valid in the case of high-voltage lines which also might impact negatively, on a very similar way, the future WSN.

7. Conclusion

In this paper we have performed a comprehensive analysis of WSNs from the energy efficiency point of view. Additionally, we have simulated a WSN in a smart agriculture application. The outcome of the both of these confirmed that the radio components of the network nodes while an active mode are the main power consumers in WSNs. The rest of the physical components of a sensor node are characterized by a significantly lower consumption. Additionally, it is confirmed that the main mechanism for reducing the consumption in the network nodes is the duty cycle mechanism. By simulating two different duty cycle mechanisms available within the Cooja simulator in the considered scenario, we came to the fact that ContikiMAC performs better then the CX-MAC and is able to reduce the time the radio is spending in active mode to around 0.9% of total operation time, which is around six times less than in the case of the CX-MAC protocol. That results in a tremendous energy savings in the simulated WSN. The other factors which have to be taken into consideration during the design and deployment of a WSN in the smart agriculture applications are also analyzed as well as their mechanisms of influence on the power consumption as a final consequence. In future designs of WSN one should consider artificial neural networks and fuzzy logic systems in order to improve control strategies of WSN (Mohammadhassani et al., 2014; Sedghi et al., 2018; Mansouri et al., 2017; Safa et al., 2016; Toghroli et al., 2018; Mohammadhassani et al., 2015).

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