Alexandru LAVRIC, Valentin POPA, Ilie FINIS, Codrin MALES

Stefan cel Mare University of Suceava

Performance evaluation of Tree and Mesh ZigBee Network Topologies used in Street Lighting Control Systems

Abstract. *The design of a high performance street lighting control system is an important issue. This paper focuses on an assessment of the performance of the ZigBee mesh and tree network topologies which, can be implemented in different street lighting control network configurations. The paper also presents the performance evaluation of three configurations in order to select the best candidate that can be integrated within a street lighting control system. The data reveal that the tree topology is much more efficient than the mesh topology. Also, the impact of the acknowledgment (ACK) communication mechanism on the network throughput and on the end-to-end delay application parameter is analyzed.*

Streszczenie. *W artykule przedstawiono wyniki analizy działania sieci w topologii siatki ZigBee oraz drzewa, w zastosowaniu do sterowania oświetleniem ulicznym. Ocenie poddane skuteczność doboru najlepszych kandydatów do integracji z systemem oświetlenia w odniesieniu do trzech konfiguracji. Stwierdzono znacznie większą skuteczność działania struktury drzewiastej w stosunku do struktury siatki. (**Ocena działania sieci ZigBee i struktury drzewiastej w systemie sterowania oświetleniem ulicznych**).*

Keywords: mesh – tree – performance evaluation – street lighting monitoring and control architecture – ZigBee.
Słowa kluczowe: oczko, trzewo, ocena działania, architektura sterowania i monitorowania oświetlenia ulicznego, ZigBee.

Introduction

A problem that should not be neglected when implementing a street lighting monitoring and control system, is the careful selection of the communications protocol that must ensure a high level of performance. The systems presented in the scientific use the types of communication protocols presented in Tab. 1 for sending information.

Table 1. Communication protocols used in street lighting control

Long range communication	Wi-Fi (802.11 standards)
	Ethernet (cable)
	GPRS (General Packet Radio Services)
	Wi-Max (802.16 standards)
Short range communication	ZigBee
	IEEE 802.15.4- based
	6LoWPAN (IPv6 over Low power Wireless Personal Area Networks)
	Proprietary RF Solutions
	UWB (Ultra-Wide Band and Ultraband)
	PLC (Power Line Communication)

The communication protocols used by street lighting control systems can be divided into two categories: local communication, using short range transmission (street lamp-to-street lamp) and long range communication such as the systems that link the command center to the sensor network [1]. The vast majority of the monitoring and control of street lighting systems proposes the use for local communication of a wireless protocol because it represents a cost effective solution. One such standard is ZigBee which is a low-cost and a LR-WPAN (Low Rate Wireless Personal Area Network) communication protocol. Fig. 1 presents the ZigBee communication protocol that defines the network (NWK) level and the APL application profiles over the MAC (Media Access Control) and physical level of the OSI model (Open Systems Interconnections) implemented by the IEEE 802.15.4 standard [2].

A ZigBee wireless sensor network can be implemented using three types of nodes: coordinator, routers and End Devices. The coordinator is an essential node in the network initialization which performs the following tasks: the selection of the radio channel on which communication is performed and the initialization of the network, allowing other nodes to join the network. In addition, the coordinator performs message routing, security management and many other services.

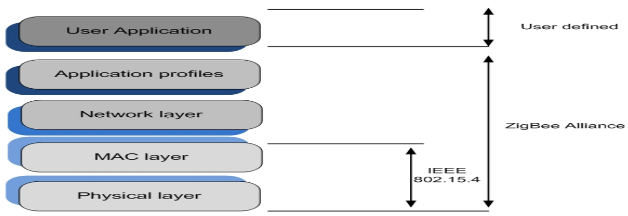

Fig. 1. ZigBee Stack

A router node can retransmit messages and allow other nodes to join the network. The main task of an End Device type device is sending and receiving messages, the latter has no routing capabilities if is of RFD (Reduced Function Devices) type, and is often powered by batteries. IEEE 802.15.4 standard defines two types of nodes: FFD (Full Function Devices) that can be coordinators or routers and RFD (Reduced Function Devices) nodes that can communicate only with FFD nodes and cannot act as coordinators. The RFD nodes are much cheaper because of the reduced RAM / ROM memory.

Another issue that should not be overlooked is the selection of the best street lighting control system architecture that would ensure a high performance level at the lowest implementation cost as well. This entails choosing the optimum number of router nodes and End Device, as well as deciding on their position within the network. In a related paper [1] the software and hardware implementation of a street lighting control system are presented in detail. The ZigBee network topologies that can be implemented in street lighting control system may be of tree or mesh type. In the scientific literature there are several papers [3]-[8] that detail the performance evaluation of these network topologies but taking into account only the node mobility problem. None of these papers assess the performance of different network configurations that can be implemented within a street lighting control system.

Street lighting control architecture

The architecture of a street lighting control system has certain specific characteristics: it is of the long-thin type, it can incorporate more than a few hundred nodes spread over a wide geographical area and it has a central point called a sink node where all the information is collected. The objectives of the paper consists in studying and determining the optimal network configuration that can be implemented in a street lighting control system in order to obtain a high performance level. The spacing between light poles in a street lighting control system is of about 50 meters. A street lighting control system entails the presence of a large number of devices spread over a wide geographical area. Due to the LOS conditions (Line-of-Sight), limited by the occurrence of obstacles, the network must be implemented in a topology that would ensure a very high performance level. The street lighting control systems that use the ZigBee wireless communication protocol are based on a long-thin structure that stretches for a few kilometers and incorporates a few hundred nodes [9].

Consequently, a series of simulations have been performed in order to validate the performance of tree and mesh network topologies. Thus, various configurations of the street lighting control network have been taken into account, by changing the position and the number of routers or End Device nodes.

Simulation setup and results

Several simulation scenarios have been considered during the simulations. For each configuration of the street lighting control network, evaluations have been conducted on the performance level reached when a mesh and, respectively, a tree type network topology has been used. The parameters analyzed are the throughput, the end-to-end delay application and the performed number of hops. Fig. 2 presents a section of the first suggested configuration that consists in a section of the simulated network.

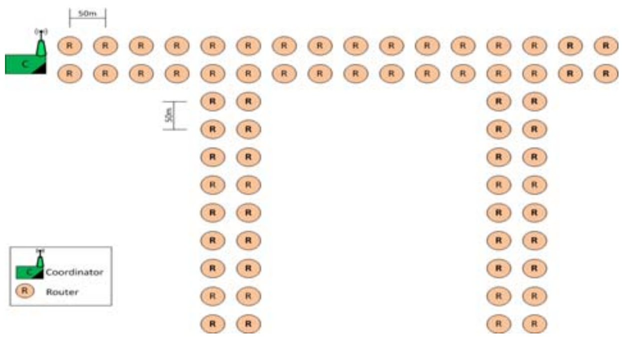

Fig.2. Network configuration 1

The disadvantage of this architecture mainly consists in the high implementation costs, as the router type nodes have a larger RAM memory and, implicitly, a higher cost. The following paragraphs present a series of configurations whose performance has been evaluated in order to determine the optimum number and position of the router and End Device type nodes within the network. Such a configuration that has been taken into account is presented in Fig. 2.

In this case, each network node is of the FFD type, i.e. routers. Additionally, the analyzed network topologies have been of the tree and mesh type, respectively.

Fig. 3 presents another configuration of the network whose performance has been evaluated. Note that the number of routers has been cut in half in order to reduce costs, but this reduction also increased the distance between the nodes that can resend the messages. Thus, the transmission power has been increased to 6 dBm during the conducted simulations.

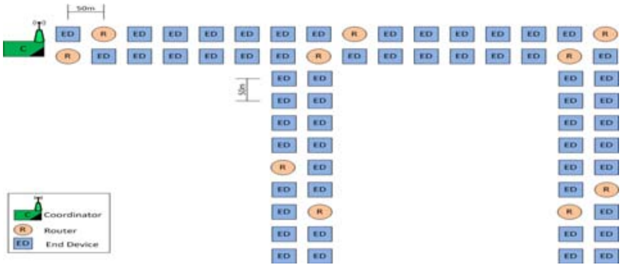

Fig.3. Network configuration 2

Fig. 4 presents the third configuration, where the router nodes are arranged diagonally. This enables a better distribution of the FFD nodes within the network.

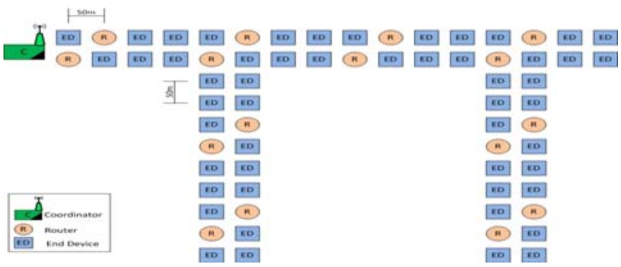

Fig.4. Network configuration 3

The third proposed configuration integrates 200 nodes, of which one is the coordinator, 75 are routers and 124 are end devices (Fig. 4). The spacing between the nodes was set at 50m, as the network has a linear pattern (long-thin), distributed on a distance of more than one kilometer. The configurations are based on the different positions arrangements of the routers which are FFD type and end devices which are RFD types. The transmit power of the nodes was set at 2.3 dBm, for the proposed configurations one and three, using the 2.4 GHz communication band in both simulated scenarios in order to be as accurate as possible. All the simulations have been conducted under the assumption that the network nodes transmit a package of 127 bytes to various receivers at a rate of one packet per second in order to simulate the traffic occurring in a street lighting control network. The simulation time is set to 5000 seconds.

Fig. 5 and 6 detail the results for the three simulated configurations in terms of end-to-end-delay and throughput that will allow the selection of the best candidate. The simulations have been developed by means of the tree and mesh network topologies. The end-to-end delay application parameter measures the delay of the packages within a network and can be calculated by determining the time interval elapsed between the moment the package was queuing for transmission on a physical level and the moment the last bit is received at the destination node [9].

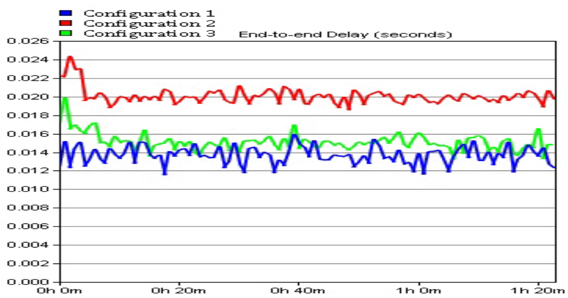

Fig.5. Tree End-to-End Delay

As expected, in terms of end-to-end delay, the first configuration ensures a high performance level, as all the nodes are of the router type. However, this configuration cannot be physically implemented due to the high costs. The lowest performance level is reached by the second configuration, where the number of routers has been reduced to half and the transmission power has been increased, the end-to-end delay of the application amounting to approximately 20ms. The configuration that reaches the optimum level in terms of the end-to-end delay parameter (15 ms) is configuration number three, where the router nodes have been arranged diagonally and have thus ensured better coverage inside the network.

The throughput parameter, measures the quantity of information properly transmitted from a source node to a destination node within a specific interval. Fig. 6 provides a graphic depiction of the throughput parameter for the tree network topology in different configurations.

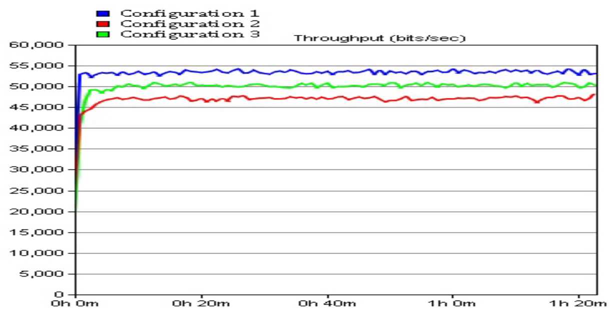

Fig.6. Tree Throughput

As can be noted in Fig. 6, the highest throughput level is recorded by the configuration with all the nodes as routers (54.000 bits/sec), followed by the third (50.000 bits/sec) and the second configuration (46.000 bits/sec). In case of a tree network topology the network load is divided between the coordinator and the local routers. Subsequently, a series of simulations have been conducted, by employing the mesh type network topology. In Fig. 7 the End-to-End Delay parameter is presented for the three mesh configurations used.

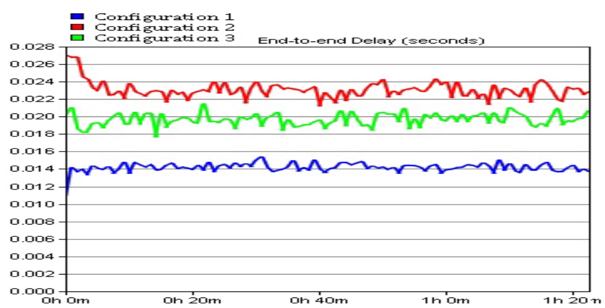

Fig.7. Mesh End-to-End Delay

The data reveal that in a mesh topology the end-to-end delay application is much higher than in a tree type network topology. The end-to-end application delay for the three configurations is approximately 14ms, 23ms and 20ms, respectively. Thus, the tree topology is recommended in a street lighting monitoring and control system. Additionally, the configuration where the routers are arranged diagonally (number three) ensures a high performance level and proves to be a very cost effective alternative. Fig. 8 presents the throughput parameter for the three configurations where the mesh network topology has been used. The third configuration achieves a higher throughput level if the tree network topology is used, as opposed to the mesh network topology.

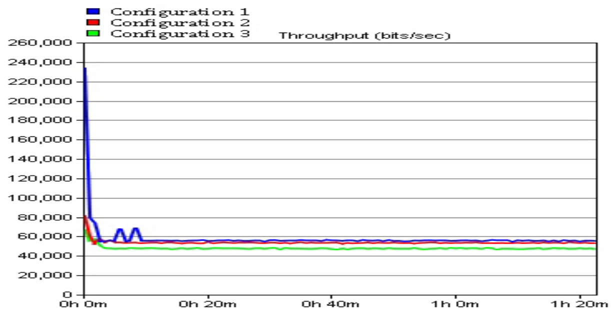

Fig.8. Mesh Throughput

Another parameter that has been measured during the simulations is the number of hops within the network, i.e. the number of intermediate nodes a package hops from the source to its destination node. Fig. 9 presents the number of hops for the third configuration, which reaches a high performance level and, implicitly, entails the lowest energy costs. In terms of hops, tree network topologies entail a much lower number and thus prove to be the most energy efficient. Therefore, the third proposed configuration is the ideal candidate in terms of implementation costs and performance level reached.

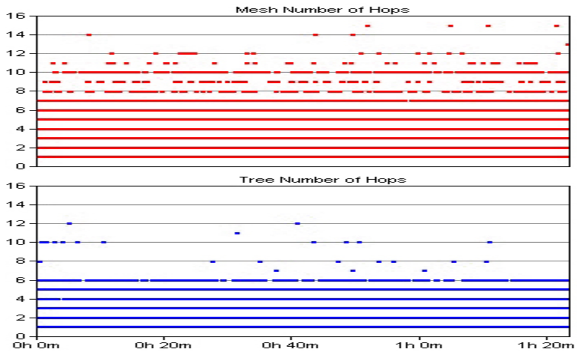

Fig.9. Number of hops (configuration 3)

The mesh topology uses routing tables compared with the tree one which is more organized and its control system is more precise due to its hierarchical structure it is based on. In case the nodes are battery-powered, the number of hops is very important, as the retransmission of a package entails a certain amount of energy consumption. Thus, the tree network topology is much more efficient than the mesh type as far as energy consumption is concerned, since the number of hops is considerably lower in the former. Another simulation scenario requires that each End Device node should send packages of 127 bytes to the nearest router node, every second, by using the communication mechanism with and without acknowledgment (ACK). The purpose of this simulation scenario of the third network configuration is to analyze the influence exerted by the use of the ACK mechanism on the network load within a street lighting monitoring and control system. In Fig. 10 and 11 the simulation results (end-to-end delay) with and without using ACK are presented. In this particular case, the performance of the two network topologies (mesh and tree) is similar, as the number of hops of the generated network traffic amounts to one. The length of the ACK is about 0.05 seconds, while the number of retransmisisons is set at 5.

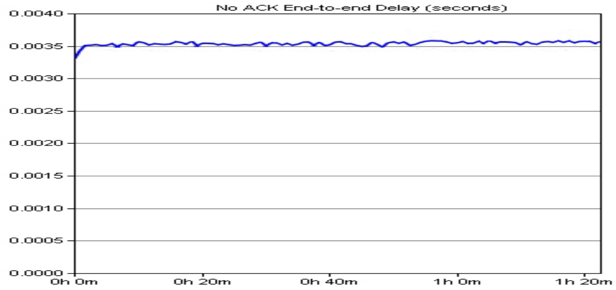

Fig.10. End-to-End Delay (No ACK)

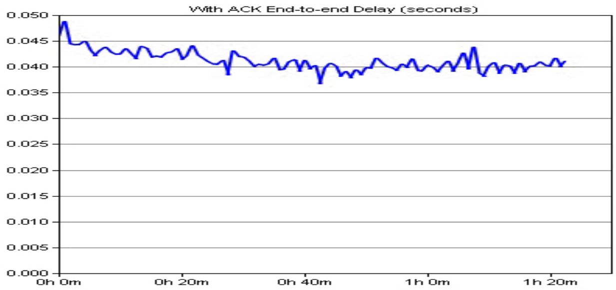

Fig.11. End-to-End Delay (With ACK)

As can be noted, the end-to-end delay parameter when using the ACK communication mechanism (40ms) is 10.43 times higher than in the case when it is not employed (3.6ms). Fig. 12 presents the throughput parameter for the case when ACK is present and, respectively, absent.

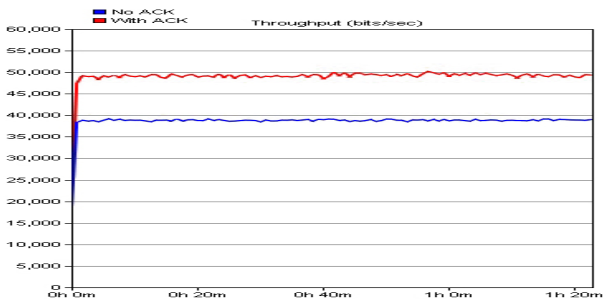

Fig.12. Throughput (ACK / No ACK)

The introduction of the ACK mechanism leads to an increased throughput, by approximately 22%. When implementing a street lighting control network of a few hundred nodes, most of the messages are of the broadcast type, when sending the on/off type commands. Thus, a passive ACK procedure must be used in order to decrease the network load and, implicitly, the number of dropped packages. The use of a passive ACK procedure, when the message is of the broadcast type, does not allow the node to confirm the successful receipt of the package. However, the network coordinator and the ZigBee routers check whether the nearby nodes have successfully delivered the message. In this case, after a node sends the message, it enters in listening and waiting mode until the respective package is resent to the nearby nodes, thus signaling the successful receipt.

Conclusions

The paper evaluates the performance of three network configurations that can be implemented in a street lighting control system. The purpose of this study was to establish the optimum configuration that would reach a high performance level and entail lower implementation costs. The network throughput has increased by approximately 22% in the presence of the ACK mechanism, as opposed to cases when it has not been used. When employing the tree network topology, the network load is divided among the coordinator and the local routers, thus reducing collisions and the number of lost packages. The tree topology performs highly better than mesh topologies when implementing a street lighting control system.

According to the obtained results, the third configuration, where the routers are arranged diagonally, reaches the highest performance level and proves to be a cost effective solution that can be implemented.

Acknowledgements

This paper was supported by the project "Improvement of the doctoral studies quality in engineering science for development of the knowledge based society - QDOC" contract no. POSDRU/107/ 1.5/S/ 78534, project co-funded by the European Social Fund through the Sectorial Operational Program Human Resources 2007-2013, and by PRO-DOCT - Contract no. POSDRU/88/1.5/S/52946.

REFERENCES

[1] Alexandru Lavric, Valentin Popa, Ilie Finis, The design and implementation of an energy efficient street lighting monitoring and control system, *Przegląd Elektrotechniczny*, (2012), nr 11, In Press
[2] www.zigbee.org
[3] Mikko Kohvakka, Mauri Kuorilehto, Marko Hännikäinen, Timo D. Hämäläinen,Performance Analysis of IEEE 802.15.4 and ZigBee for Large-Scale Wireless Sensor Network Applications, *International workshop on Performance evaluation of wireless ad hoc, sensor and ubiquitous networks*, (2006), 48–57
[4] Peter Brida, Juraj Machaj, Frantisek Gaborik, Norbert Majer, Performance analysis of positioning in wireless sensor networks, *Przegląd Elektrotechniczny*, (2011), nr 5, 257-260
[5] Schmid, T., Shea, R., Srivastava, M. B., Dutta, P., Disentangling wireless sensing from mesh networking, *Proceedings of the 6th Workshop on Hot Topics in Embedded Networked Sensors*, (2010), 1-5
[6] Zhiping Fan, Zhengzhe Jin, A Multi-weight Based Clustering Algorithm for Wireless Sensor Networks, *Przegląd Elektrotechniczny*, (2012), nr 1b, 9-21
[7] Huang Y., Pang A., Hsiu P., Zhuang W., Liu P, Distributed Throughput Optimization for ZigBee Cluster-Tree Networks," *IEEE Transactions on Parallel and Distributed Systems*, (2012), 513–520
[8] Igor Kurytnik, Mikołaj Karpiński, Marek Aleksander, Mariusz Mikulski, Algorithms of topology building in the Wireless Sensor Networks, *Przegląd Elektrotechniczny*, (2009), nr 4, 22-24
[9] Alexandru Lavric, Valentin Popa, Codrin Males, Ilie Finis, "A Performance Study of ZigBee Wireless Sensors Network Topologies for Street Lighting Control Systems", *International Workshop on Mobile Ad-Hoc Wireless Networks*, (2012), 130-133

***Authors**: Alexandru Lavric (PhD. Student), Department of Computers, Electronics and Automation, Stefan cel Mare University of Suceava, Universitatii str. 13, 720229 Suceava, Romania, E-mail: lavric@eed.usv.ro;*
Prof. Dr Valentin Popa, Department of Computers, Electronics and Automation, Stefan cel Mare University of Suceava, Universitatii str. 13, 720229 Suceava, Romania;
Finis Ilie (PhD. Student), Department of Computers, Electronics and Automation, Stefan cel Mare University of Suceava;
Codrin Males (PhD. Student), Department of Computers, Electronics and Automation, Stefan cel Mare University of Suceava.