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Evaluation of quality of service provisioning in large-scale pervasive and smart collaborative wireless sensor and actor networks

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ABSTRACT

With the production of low cost sensors, classical concept of Wireless Sensor Networks (WSNs) evolved into large-scale concept hosting thousands of nodes within a network and generating abundant quantities of data. As these networks are being continuously developed a new class of WSNs are proposed: Wireless Sensor and Actor Networks (WSANs). These networks introduce the actuating component, alongside with the sensing component, where QoS is becoming a very significant factor. The authors of this paper approach the problem of QoS support in large-scale WSAN from a physical layer, where the deployment parameters effects on QoS metrics are demystified. The analysis is formulated on two scenarios: worst case scenario (all nodes transmit data towards the network sink) and best case scenario (a single node transmits a stream of data towards a network sink). For both scenarios two routing protocols were compared, a simple flooding algorithm and a simple distance vector protocol. Also, a new relation between hop count and latency based on transmission power is observed, not reported in the available literature, resulting in a new proposed empirical latency model.

1. Introduction

Today more than 9 billion electronic devices are present on the planet, and according to some forecasts there will be more than 24 billion devices in 2020 [15]. This fact reflects on the rapid evolution of the ICT and in that concept, the Internet of Things. A sheer volume of currently interconnected devices within the Internet causes vast amount of information to be exchanged between the devices themselves (Machine to Machine communication, M2M) and between people and devices [7]. One of the influencing factors for the exponential growth of devices is their simplicity, low cost and the ability to use wireless communication for exchanging information. This propelled a rapid development of small devices which started a new era of applied Wireless Sensor Networks. A large-scale Wireless Sensor Network is a wireless network composed of a large number of sensor nodes. These nodes are affected by a limited power supply, limited processing capabilities and a limited communication range [23,13]. With the rapid development of WSNs in domains such as process control, industrial automation and related domains, a new class of WSNs are coming into focus: Wireless Sensor and Actor Networks (WSANs). These networks introduce the actuating component, alongside with the sensing component [37]. In WSANs besides sensing tasks, acting tasks are present, resulting in the capability of performing actions in real world, rather than just observing [3].

A WSAN is often designed for a specific task completion and the specific application [40,35], but in various scenarios it can be used as a generic communication infrastructure. The ubiquity of WSANs and their integration in the IoT started to increase with the reduction of WSAN hardware cost and the omnipresence of the Internet infrastructure. The term, large-scale WSAN describes a network with densely distributed nodes within a wide area of interest, which expands classical network concepts. With the increase in the number of nodes and increased spatial density, communication aspects of large-scale WSANs are more demanding (increased interference, a larger number of data hops, etc.). On the other hand, applications of newly formed large-scale WSANs usually involve challenging computations and the need for real-time communications with strict maximum end-to-end latency. With the proliferation of WSANs in almost every existing field of applications, new classes of WSAN based applications with different characteristics (process control, industrial automation, visual surveillance, military applications (target tracking), monitoring of hazardous environment and so forth) that demand real-time requirements like bounded end-to-end delay and high reliability, which represent a concept of Quality of Service support [10,13,12]. Although modern computer networks support QoS differentiation by default, the

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same cannot be stated for WSANs. If compared to WSN the QoS requirements in WSAN are differently set. First and foremost, WSANs are a heterogeneous networks consisting of low powered sensors and actors (often grid powered). Next, WSANs are different by concept as the communication in WSAN is referred to as coordination, and various coordination models exist. Often the coordination is between actors (actor-actor coordination) that represents a very different communication model compared to WSN. Finally, the data sent through WSAN is often a high priority data that cannot be aggregated or compressed, so classical congestion mitigation models from WSN are not applicable to WSAN [37].

Motivation for conducting in-detailed analysis of these factors affecting QoS in large-scale WSANs emerged from the fact that mathematical modelling of large-scale WSANs is a non-trivial task. The performance of the network must be often analyzed from a probabilistic or empirical point of view. The research of QoS support in large-scale WSANs is accompanied by a large variety of issues that need to be addressed before the problem of QoS in large-scale WSANs can be resolved. From a layered point, physical layer of the OSI model is the first link affecting the overall QoS in the network. In classical wired networks, these problems are mitigated by establishing reliable communication at the physical layer, while in WSANs this is not the case. Varying characteristics of radio channels (fading, shadowing, etc.), transmission power due to energy depletion and the initial placement of nodes (deployment parameters) within the network result in variations in the overall QoS in the network. Furthermore, communication protocol and protocol parameters have a profound effect on the overall network QoS. The choice of a Medium Access layer or routing protocol can improve or diminish QoS in a network [34,30]. Thus a systematic analysis on the basic protocols must be conducted before new protocol development is pursuit.

Consequently, the authors approach the problem of QoS support in large-scale WSANs taking into account deployment parameters and communication parameters (transmission power, routing protocol and packet generation intensity). As our previous work in Horvat et al. [20] presents the preliminary analysis where a direct influence of deployment parameters on QoS in large-scale WSANs was observed (deployment parameter is related to node deployment density and number of nodes), this paper investigates the impact of node density and transmitter power value alongside with routing protocol and packet generation intensity on QoS in a large- scale WSAN, representing a holistic approach. In our testbed two routing protocols are compared for both scenarios, a simple flooding algorithm and a simple distance vector protocol. The analysis was performed for two scenarios: worst case (all nodes are transmitting data) and best case (a single node transmits data). The resulting QoS metrics that were used as QoS indicators were latency, packet delivery ratio and network throughput.

From the conducted simulation approach this paper gives the following contributions: **Comprehensive analysis of QoS provisioning in WSANs for various deployment parameters and different protocols/parameters** (for various deployment parameters, two routing protocols and different transmitter power); **Correlation analysis for worst case (congested) and best case WSAN** (correlation between the average hop count and the latency exists only for lower transmitter power values); **New empirical latency model based on transmitter power and hop count** (new relation between hop count and latency based on transmission power is observed for best case scenario, not reported in the available literature).

The paper is structured as follows: Section 2 discusses Wireless Sensor and Actor Networks whereas Section 3 presents the related work from the field. Section 4 elaborates QoS in WSANs and proposes metrics for monitoring QoS in WSANs. The influence of various parameters on QoS metrics in WSANs is shown through simulation that was carried out in two scenarios in Section 5. The contribution of this paper is shown through modeling of the latency by a novel model compared to the average hop count, which is then compared with the simple linear model widely used in research. Section 6 concludes the paper by giving an overview of our contributions and guidelines for future research.

2. Wireless sensor and actor networks

With the development of WSNs and the development of new technologies, wireless sensor nodes are being reduced in size and becoming more advanced and more effective. Nevertheless, the concept of wireless sensor networks is not without flaws. The difference between WSNs and the classic computer networks (such as dynamic topology, wireless communications, asymmetric traffic, redundancy of data, limited resources, and a large number of hops routing) led to many problems that still have not been eliminated. The problem of the limited amount of energy and limited processing capabilities remains, which distinguishes them from conventional computer networks. In recent years wireless sensor networks with an extremely large number of sensor nodes ranging up to 10,000 nodes in the network emerged due to the low manufacturing costs and wide applications of wireless sensor nodes [36]. In such large networks even simple functions such as sending data from source to destination pair are difficult, especially taking into account the unreliability of the radio communications itself. Therefore, a decade after their introduction in the development and research in the field of WSNs is not slowing down.

Although today's wireless technologies developed to a very high level, it must be taken into account that even today there are certain applications where wireless communication still does not provide sufficient quality of service (QoS), such as, in industrial plants that require high reliability and where there are limits in the acceptable delay values in the transmission of data through the network. The new concept of Industry 4.0 extends the existing knowledge of Internet of Things (IoT) and WSNs into a new concept that advocates the reliable real-time communications applicable to existing industries.

Furthermore, very well-known structures and sensor networks that are used for data collection from the observed environment are evolving into advanced and complex networks for the purposes of the forthcoming applications. Usually the sensor nodes were used for measuring temperature, light intensity, vibration, sound, radiation, etc. Lately there is a need not only to measure values that describe the environment but to also affect the environment in order to control it. In this process active elements called actuators were added to wireless sensor nodes so that the nodes would not be only used for sensing purposes. That presents a departure from the classical concepts of WSNs. These types of wireless sensor network which have nodes that include not only the sensing element (sensor), but the active element (actuator, actor) as well are called Wireless Sensor and Actor Networks (WSAN), Fig. 1. Those networks have a response to a specific action obtained by the sensor [39,3].

Compared to the WSNs, the main difference is that WSANs have actuator nodes that consist of sensor element and the active element. Depending on the configuration type, the nodes in the WSANs can be used only as a sensor, as an actuator or as a combination of these features. Generally, there are two WSAN architectures: fully automatic and semi-automatic architecture. In fully automatic architecture actor nodes communicate with each other without direct connection with the central network coordinator. In the semi-automatic architecture communication takes place over the network coordinator. Although semi-automatic architecture has characteristics that are most similar to WSNs, due to the