Quality of Service in Wireless Sensor Networks: A Survey and Related Patents

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QoS in WSN

Abstract: Rapid advances in Wireless Sensor Networks (WSNs) indicate that they are becoming increasingly complex. Consequently users and applications are becoming more demanding. Due to unique characteristics of WSNs, like small dimensions and limited resources and capabilities, Quality of Service (QoS) is imposed as one of the key factors of WSNs. In this paper, we surveyed two main approaches for QoS provisioning in WSNs: layered and cross-layer approach. QoS provisioning with layered approach is surveyed in three WSN layers: MAC, network and transport layer. Current developments show that they can be efficiently used for QoS provisioning. However, they consider QoS only as layer specific isolated set of problems and they are highly dependent on the performance of other layers. Cross-layer approach does not have the restrictions as layered approach and hence can dispose with information from all layers of the communication protocol stack. Although it has huge potential to become the most efficient solution for QoS provisioning in WSNs, current development indicate that there are still many issues and challenges that need to be overcome. Since the concept of the QoS is relatively new in WSNs, there are not a large number of patents currently dealing with this issue, however but in coming years a large increase in the number of such patents is expected. Available patents in this domain are described in the paper.

Keywords: Cross-layer approach, Quality of Service (QoS), Wireless Sensor Network (WSN).

1. INTRODUCTION

Technology development in the areas of miniaturization and wireless connectivity has led to the rapid development of Wireless Sensor Networks (WSNs). Due to the versatile usages such as environment observation, vehicle traffic monitoring, habitat monitoring, industrial automation, health applications, etc., WSNs are becoming the primary research field of many scientists. Most research is related to the architecture, protocols, energy consumption, optimization and Quality of Service (QoS) in WSNs. Since WSNs consist of wireless nodes, they mostly use batteries as primary power source. Therefore, most traditional protocols are dealing with issues of energy conservation and prolonging network lifetime. At the beginning of the WSN development, QoS was not given much attention, but with the appearance of critical, multimedia and real-time applications, QoS is becoming increasingly significant. Furthermore, WSNs have an increasing number of users and applications that require guaranteed WSNs performances.

Due to limited resources, versatile usage and various applications, WSNs should be [1]:

- Energy efficient: Energy consumption must be highly constrained.
- Application tailored: WSNs should support wide variety of applications.
- Scalable: WSNs with huge amounts of nodes should operate normally.
- Secure: WSNs should ensure data robustness, integrity and confidentiality.
- Long term: Network lifetime should be very long.

As described in [1], the working cycle of a WSN can be divided into three phases:

- Birth phase: Startup of a WSN. Includes initial organization, configuration and optimization. Since this phase could be highly energy consuming, it is necessary to develop initialization protocols with minimum energy consumption. Owing to the fact that it is application dependent, it can be defined in several ways:
    - At least one node communicates with at least a one data collecting unit.
    - The entire communication structure has been set-up in a fully connected fashion.
    - A given percentage of the network is capable of communicating.

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- Life phase – the WSN is in full working mode; it performs detection, sensing, reporting and data transmitting. The main goal in this phase is to maintain a predefined QoS.
- Death phase: This phase starts with node failures, energy drainage, drastic topological changes or malicious attacks. However the beginning of the death phase is different for different applications. The death phase could start with:
    - Failure of the first node.
    - Failure of the last node.
    - Lowering the QoS.

Since WSNs are mostly used in difficult to access areas, the primary power source for most WSNs is a battery. Furthermore, sensor nodes are mostly small and therefore, it is difficult to implement other power supplies such as solar panels or wind turbines. WSNs resources are constrained and the main concern is the limited amount of energy which causes short communication range, low bandwidth, and limited processing and storage in each node. Different types of WSNs have different challenges and constraints. As described in [2], there are generally two types of WSNs:

- Structured,
- Unstructured.

Unstructured networks have a lower deployment cost. However, the advantage of structured networks is deterministic deployment. Therefore, all desired regions are properly covered which leads to the lower network maintenance and management costs.

Depending on the environment, there are five different types of WSNs [2]:

- Terrestrial: Can be structured or unstructured. Usually contain a large number of nodes powered with batteries and consequently energy conservation is very important.
- Underground: Sensor nodes are placed underground or in caves or mines and are equipped with batteries. Once they are placed it is difficult to access them. Therefore, the deployment requires careful planning and energy and cost consideration.
- Underwater: Due to the fact that sensor nodes are equipped with limited batteries which cannot be replaced since they are deployed underwater, energy consumption needs to be as small as possible. Most energy is spent for an underwater acoustic communication due to the unique characteristics of the underwater acoustic communication channel, such as limited bandwidth, long propagation delay and signal fading issue.
- Multi-media: Sensor nodes are equipped with cameras and microphones and usually deployed in a pre-planned manner. Since they are delivering multi-media content such as video, audio and images, they require high bandwidth, QoS provisioning and they have high energy consumption.
- Mobile: Sensor nodes have the ability to move, reposition and organize itself in the network. Therefore, they can achieve a higher degree of coverage and connectivity compared to static sensor nodes. Data delivery is often a challenging task and it could consume high amounts of energy since dynamic routing is used.

QoS provisioning is important in all five types of WSNs. Furthermore, in all five types, sensor nodes could report a sensed data on a regular basis, on event basis or in real-time. This depends on a type of application used in WSNs. As a result of versatile usage, a wide range of applications can be used in WSNs. They can be classified into two categories which each has specific characteristics and requirements:

- Monitoring applications: Include indoor/outdoor environmental monitoring, health and wellness monitoring, power monitoring, inventory location monitoring, factory and process automation and seismic and structural monitoring.
- Tracking applications: Include tracking objects, animals, humans and vehicles.

QoS is defined differently from the users and applications perspective and differently from the network perspective, as described in [3]. Users are only concerned with the network services that directly impact the quality of the application, while from the network perspective it is important to provide the desired QoS and in the same time, efficiently utilize network resources. Due to the above mentioned reasons and some unique characteristics of WSNs, such as limited resources, large-scale random deployment and novel data centric communication protocols, it is difficult to define unique QoS parameters for various types of WSNs. In the literature [3, 4], authors propose different solutions to this problem.

Generally, there are two main approaches for QoS provisioning in WSNs: layered and cross-layer approach. The outcome for both is the same: providing predictable QoS levels to users and applications and in the same time lowering energy consumption. In this paper we focus on the QoS provisioning in the three WSN layers: Medium Access Control (MAC), network and transport layer, and through cross-layer approach. We start with description of QoS support in WSNs.

Then, we survey existing protocols in the literature and describe QoS metrics and mechanisms for both layered and cross-layer approaches. Additionally, we discuss the open issues on QoS provisioning and address some challenges. Furthermore, we provide a detailed description of available patents in this domain. We conclude the paper with discussion on current and future developments.

The remainder of this paper is organized as follows: First Section II describes QoS support in WSNs. Section III details QoS provisioning in MAC, network and transport layers. Cross-layer approach for QoS provisioning in WSNs is given in Section IV. Section V reviews patents in this domain. Section VI concludes the paper by outlining current and future work in the field.

2. QOS SUPPORT IN WSNS

In recent years, one of the main goals for researchers is how to provide the desired QoS to users and applications in WSNs and in the same time reduce energy consumption and consequently prolong network lifetime.

Mission critical and real-time applications require performance guarantees from the system on which they are implemented [5]. With their emergence in WSNs the issue of QoS appeared. As described in [4], the QoS is an umbrella term for a collection of technologies that allow network-aware applications to request and receive predictable service levels in term of QoS requirements. These predictable service levels can be provided through a set of measurable service parameters, which are presented below.

QoS in Traditional Networks

In traditional networks, like Internet, the QoS can generally be obtained through the network over-provisioning, traffic engineering, and differential packet treatment inside routers, as described in [6]. Traditionally, the emphasis is on maximizing end-to-end throughput and minimizing delay. Over-provisioning of network resources is based on adding huge amounts of resources in the network. However, bandwidth availability and router capacity are not infinite resources and excess resources are expensive, especially in wireless networks. Traffic engineering takes into account available resources and expected traffic on various network links and some paths can be over-provisioned and used for the most demanding packet flows, while others could be left for the best effort traffic. With differential packet treatment inside routers, QoS is assured via adequate packet classification, queuing, and scheduling inside routers. WSNs are fundamentally different from traditional networks because WSNs devices are small and have limited resources and capabilities. Therefore, QoS based protocols from traditional networks cannot be efficiently used in WSNs. As a result, new QoS parameters and requirements for WSNs are defined.

QoS Challenges in WSNs

The most important QoS challenges in WSNs are addressed below:

- Limited resources and capabilities: QoS methods must be aware of limited resources and capabilities in WSNs such as limited energy, bandwidth, memory, and processing and communication capabilities. Furthermore, there should be balance between QoS level and energy consumption.
- Node deployment: Unstructured networks have lower deployment cost than structured networks. However, deterministic deployment solves problems of neighbor and path discovery and as a result QoS methods have available geographical information of the nodes.
- Dynamic network topology: It is standard challenge for mobile WSNs. However, almost all WSNs have dynamic topology due to link failures, node power failures, or different power management mechanisms. QoS should not be affected with network topology changes.
- Scalability: QoS should not be affected with increasing or decreasing in number of nodes in WSNs.
- Multi-source multi-sink systems: The best examples are wireless sensor-actuator networks that besides standard challenges, have issues on platform heterogeneity, service-oriented architecture, resource self-management and security requirements [7]. The state-of-the-art for QoS in Wireless Sensor-Actuator Networks (WSANs) in the context of critical infrastructure protection can be found in [8].
- Various types of applications: Due to widespread use of WSNs, there are a large number of WSNs applications with various QoS requirements. The most demanding application can be found in:

- Real-time WSNs: Performance-critical applications like intruder tracking, fire monitoring and medical care are mostly used in real-time WSNs. They have high requirements on bandwidth, delay guarantees and delivery time. Real-time QoS guarantees can be categorized into two classes [9]: Hard Real-Time (HRT) and Soft Real-Time (SFT) guarantees. HRT systems must have deterministic bounded delay on the packet delivery and the arrival of the message after its deadline is considered a failure of the system. HRT systems require guaranteed medium access delay in each single-hop and routing delay in multi-hop. HRT is often difficult to achieve due to wireless link unreliability. SRT systems are delay tolerant but have probabilistic end-to-end delay guarantee.
- Multimedia WSNs: Deliver video and audio streams, still images and scalar sensor data. Therefore, they are bandwidth hungry, needing high throughput, low delay and data redundancy. It also requires predefined QoS level in order to successfully deliver multimedia content.

- Various traffic types: Traffic load depends on the amount of data generated by the node. QoS method should be equal effective during peak and low traffic periods.
- Wireless link unreliability: The wireless links among the sensor nodes can be easily affected by various environmental factors. Shorter links appears to be more reliable than longer links.
- Data redundancy: Is very important in multimedia and real-time WSNs. However, it is usually reduced with different data aggregation technologies [10]. Otherwise, it should be taken into account in QoS methods.

QoS Metrics in WSNs Layers

QoS provisioning in individual layer depends on layer capability. Therefore, each layer has layer specific parameters that are used for performance evaluation and QoS assessment. In Table 1 QoS parameters are assigned to each layer in a WSN, as described in [4]. Since different combinations of proposed parameters could define different QoS levels, WSNs could be categorized and could provide predictable performance.

Table **1** QoS parameters in WSNs layers.

WSNs Layers	QoS parameters
Application layer	System lifetime Response time Data novelty Detection probability Data reliability Data resolution
Transport layer	Reliability Bandwidth Latency Cost
Network layer	Path latency Routing maintenance Congestion probability Routing robustness Energy efficiency
Connectivity maintenance layer	Network diameter Network capacity Average path cost Connectivity robustness Connectivity maintenance
Coverage maintenance layer	Coverage percentage Coverage reliability Coverage robustness Coverage maintenance
MAC layer	Communication range Throughput Transmission reliability Energy efficiency
Physical layer	Depend on capabilities of sensor components (sensing, data processing and communication component)

Application Specific QoS Parameters

Due to the large number of applications and widespread use of WSNs, QoS provisioning requirements are diversified. However, as described in [3], primary application specific QoS parameters are:

- Coverage: Determined by the specific requirements during the deployment of sensors.
- Exposure: Determines how well an object can be observed over a period of time.
- Measurement errors: Determined by the measurement precision of sensors.
- Optimum number of active sensors.

Network Specific QoS Parameters

From the network perspective, it is important to effectively utilize network resources, whilst concurrently delivering QoS constrained data from sensors. Since numerous applications have common requirements, they are divided into three data delivery models, as described in [3]:

- Event-driven model: Most applications in this model are interactive, do not tolerate delays, are determined by the task and not end-to-end applications. Furthermore, the data obtained from the sensors mostly contain much redundancy, though data generated by a single sensor may be of very low intensity. Response action must be quickly and reliable.
- Query-driven model: Most applications in this model are interactive, query-specific delay tolerant, mission critical and not end-to-end applications. Queries could be sent on demand and also used to manage and reconfigure sensor nodes. Data is pulled by the sink.
- Continuous model: Data from the sensors are continuously sent to the sink at a predetermined rate. When transferring video, image or audio data in real-time, following conditions must be satisfied:
    - Delay must be constrained.
    - Certain bandwidth requirements must be fulfilled.
    - Packet loss can be tolerant but only to a certain extent.
    - Applications must not be end-to-end.

  When transferring non real-time data, delay and packet losses are tolerated.

Since different applications have various requirements, in some networks it is necessary to use a combination of the above models, the hybrid model. As a result of the fact that most applications in WSNs are not end-to-end applications, new collective QoS parameters can be defined:

- Collective latency: Difference in time between generation of first packet and arrival of the last packet to the sink (for one event).
- Collective packet loss: Number of loss packets during information delivery (for one event).
- Collective bandwidth: Bandwidth that the reporting of the event requires.
- Information throughput: At the sink from a set of correlated sensors.

3. QOS PROVISIONING IN WSNS LAYERS

WSNs have two main approaches for QoS provisioning: classic layered approach and cross-layer approach. Layered approach achieves QoS provisioning with protocols that operate only in one individual layer of the WSN communication protocol stack, while cross-layer approach provides the desired QoS through the simultaneous interaction of multiple layers in WSN.

QoS provisioning goal for all layers of the communication protocol stack is equal: Providing the desired QoS level to applications and users while decreasing energy consumption, and consequently prolonging network lifetime. Efficiency of the QoS provisioning mechanism in individual layers depends on layer capabilities. QoS metrics usually include: bandwidth, throughput, latency, delay, jitter, packet loss and coverage. However lately energy consumption is becoming standard part of QoS metrics.

QoS provisioning in the MAC, network and transport layer is surveyed below. Since the MAC layer is the bottom layer, it has a huge impact on QoS provisioning in the upper layers. Therefore, it must guarantee one or more performance metrics to upper layers. Protocols in each layer are isolated and do not alter the protocols in upper or lower layers.

MAC Layer

Since the MAC layer is the bottom software layer, performance of all upper layers are depending on the MAC layer components and performance. QoS support in the network or transport layers cannot be provided without the assumption of a MAC protocol which solves the problems of medium sharing and supports reliable communication [11]. Therefore, QoS provisioning in MAC layer is of significant importance for overall QoS in WSN.

QoS metrics that can be fulfilled at the MAC layer are the following [11]:

- Minimizing medium access delay.
- Minimizing collisions.
- Maximizing reliability.
- Minimizing energy consumption.
- Minimizing interference and maximizing concurrency (parallel transmissions).
- Maximizing adaptivity to changes.

QoS mechanisms that can be used at the MAC layer are the following [11]:

- Adaptation and learning: Adapts operation parameters of the sensor nodes to the current network condition in order to accommodate traffic load in a more efficient way. Over time, learning algorithms could predict network changing and take necessary adaptive operations.
- Error control: Reduces consumption, whilst providing reliable and fast delivery of the sensor data. It can be implemented in each layer of the communication protocol stack.
- Data suppression and aggregation: Reduces traffic load of the network and consequently minimizes radio communication, preserves energy and

increases bandwidth. It can also be implemented in each layer of the communication protocol stack.

- Power control: Adjusts transmission power of the sensor nodes to the minimum power required for successful transmission. It is implemented in MAC layer as a joint physical-MAC layer solution.
- Clustering: Simplifies the synchronization and coordination by grouping set of neighboring sensor nodes. Consequently, it lowers energy consumption and improves reliability.
- Service differentiation: Prioritizes network traffic based on several criteria, and then forms several traffic classes. Different QoS levels are provided to different traffic classes.

In [12], authors reviewed several aspects on QoS provisioning at MAC layer. They conclude that an approach based on quantitative modeling of energy-efficiency vs. delay trade-off, based on information theoretic and wireless communications principles, is promising. However, multimedia, critical and real-time WSNs should not have delay-constrained communication. Therefore, it could be difficult to found the right balance between delays and energy consumption.

In [13], authors developed a novel Scalable QoS MAC (SQ-MAC) protocol that guarantees QoS to multimedia traffic, still images and scalar sensor data in multi-hop WSN. SQ-MAC is divided into four periods:

1. Synchronization period: All nodes are synchronized at initial stage.
2. Random access period: Three reservation procedures are operating: (i) Reservation set starts when multimedia streaming traffic is generated. All the neighbor nodes of the sender and receiver must record the reservation control packets in their own reservation tables. (ii) Reservation cancel starts when transmission is over or when node timeout has expired. (iii) Reservation recovery starts in the case of node failure.
3. Switching period: If reservation tables among neighbor nodes are different due to unstable wireless channel and collisions among the reservation control packets, the specific nodes should broadcast the slot information to maintain the reservation table accuracy among the neighbor nodes.
4. Adaptive scheduled access period: Each sending node sends the data and receives ACK message according to the order in the reservation table.

Authors performed performance analysis and conclude that SQ-MAC protocol shows improvement in terms of end-to-end delay, jitter and throughput. However, due to high frequent communication between the nodes, which is necessary for successful implementation of reservation procedures, proposed protocol appears to have high energy consumption. Although authors did not analyze the energy characteristic of proposed protocol, they announced that they will in the future. Additionally, it would be desirable to include adaptation and learning, and data suppression and aggregation mechanisms in SQ-MAC protocol, since they could reduce network traffic and lower energy consumption.

In addition, novel and interesting QoS aware MAC protocols can be found in [14, 15, 16]. In [14], authors proposed novel MAC protocol for supporting mobile clusters in WSNs. Unlike previous protocols, Mobile Cluster MAC (MCMAC) protocol supports moving clusters like Wireless Body Area Network (WBAN) in which nodes are mobile and several nodes move together at once. MCMAC protocol dedicates a part of the active slot to the mobile clusters, called the Mobile Cluster Slots (MCS). Since static sensor nodes are listening to the MCS part, MCMAC does not need adaptation time after movement of clusters. Simulation results show that MCMAC is QoS-aware in terms of the overall latency, collisions and power consumption of the network. Since this protocol seems to be promising, more simulation and real experiments are desirable. RoMAC [15] is localized QoS-aware MAC protocol that can be used in dynamic and challenging environments. Similar to MCMAC protocol, described in [14], the transmission schedule of each node is determined by its frame set and its transmittable slot in each frame. Consequently, RoMAC achieves resilience to topology change and is traffic adaptive in dynamic environments. Furthermore, it provides persistent QoS support in terms of timeless, packet jitter and fairness. Priority-based QoS MAC (PQMAC) protocol [16] divides data into classes according scenario, application, and transmission type. Every class has its own priority level and high-priority data are placed into a high-priority queue and low-priority data are placed into a low-priority queue. Therefore, high-priority data have the opportunity to be sent during any listen time. For QoS provisioning, PQMAC uses three schemes. First, doubling scheme adapts additional listen time for high priority data. Second, advanced wake up scheme calculates node's probability of receiving high-priority data and if the node has a low probability of receiving high-priority data, it remains in the sleep state to reduce energy consumption. Third, dynamic priority listen-scheduling changes the listen/sleep state based on network traffic conditions. Simulation results show that PQMAC reduces latency while maintaining energy efficiency.

Network Layer

Routing protocols are implemented primarily in the network layer and they are in charge of discovering and maintaining the routes in the network. Most of the routing protocols designed for WSNs consider energy efficiency as the main objective, with the assumption that data does not have stringent QoS requirements [17]. They can be classified as data-centric, hierarchical, location-based or network-flow protocols.

In data-centric protocols, queries are posed for specific data and routing is performed using the knowledge that is aggregate or meta-data. Hierarchical protocols minimize energy consumption by dividing nodes into clusters. Location-based protocols take advantage of the location information to make routing techniques more efficient. In network-flow protocols, route step is modeled and solved as a network-flow problem.

QoS metrics that can be fulfilled at the network layer are the following:

- Minimizing path latency/delay.
- Maximizing routing reliability.
- Minimizing energy consumption.
- Minimizing congestion probability.
- Providing effective sample rate.

Routing QoS techniques are:

- Multipath routing: Ensures delivery of QoS and improves reliability in data delivery by sending multiple copies of each packet through multiple paths from source to sink.
- Minimum cost forwarding: Finds the minimum cost path in a large WSN.
- Energy aware routing: Finds a least cost and energy efficient path that meets end-to-end delay.
- Maintaining low routing control overhead: Reduces the control overhead by minimizing the transmission of unnecessary control packet.
- In-network data aggregation: Reduces the number of transmissions/receptions in the network, and consequently preserves energy and increases bandwidth. It can be used in conjunction with delay constrained routing.
- Differentiation routing: Differentiates QoS requirements according to the data type and provides customized QoS metrics for each traffic category.

In [18], authors developed novel QoS localized routing protocol, which is designed using a modular approach, based on differentiation routing. It uses traffic differentiation while considering three different QoS parameters: (i) Energy efficiency (including both residual energy and the required transmission power); (ii) Reliability; and (iii) Latency. Considering these requirements, data traffic can be classified as:

- Regular traffic: Has no specific data-related QoS need.
- Reliability-sensitive traffic: Should be delivered without loss but can tolerate reasonable delay.
- Delay-sensitive traffic: Should be delivered within deadline but may tolerate reasonable packet loss.
- Critical traffic: Requires both high reliability and short delay.

Proposed protocol is composed of five modules following the traffic classification. These modules are:

1. Neighbor manager: It is responsible for sharing information related to the node such as its position, residual energy, estimated waiting time for each queue, estimated transmission delay, required transmission energy toward it, and estimated packet delivery ratio, among neighboring nodes.
2. Energy module: It is responsible for routing packets, when more than one candidate satisfy the required QoS criteria. It considers both the residual energy and the required transmission power.
3. Reliability module: It is responsible for increasing reliability by using multisink single-path approach.
4. Latency module: It is responsible for computing velocities of neighboring nodes.
5. Queuing manager: It is responsible for assigning priorities to packets through a multi-queue priority policy.

Proposed protocol is compared with other QoS routing protocols, namely, SPEED [19], MMSPEED [20] and DARA [21] and performance evaluation was performed in scenario of 900 nodes with critical and regular packets. Simulation results shows that proposed protocol is effective and ensures lowest latency and highest reliability while considering energy consumption. Consequently, this protocol seems to be a very promising solution for ensuring QoS in WSNs with different data traffic types.

In addition, novel and interesting QoS aware routing protocols can be found in [22, 23, 24]. QoSNET [22] is a multipath routing protocol designed for large scale heterogeneous WSNs. It is based on separation of the nodes into two sub-networks. The first is used for signaling operations and routing decisions, and the second is used for routing operations. Simulation results show that QoSNET can meet hard QoS constraints and extend network lifetime. EQSR [23] is multipath routing protocol that performs routes discovery using multiple criteria such as energy remaining, remaining buffer size and signal-to-noise ratio. It increases throughout and reduces the end-to-end delay by distributing the traffic amongst the available paths, maximizes the network lifetime through balancing energy consumption across multiple nodes and employs a queuing model to handle both real-time and non-real-time traffic. In [24], a biologically-inspired algorithm was used for QoS support in Wireless Multimedia Sensor Networks (WMSNs). AntSensNet routing protocol is based on traditional ant-based algorithm and it meets application QoS requirements and improves network performance in terms of delivery ratio, end-to-end delay and routing overhead.

Transport Layer

Transport protocols run over the network layer protocols. They are designed to control source transmissions, and to provide reliable message delivery and congestion control.

QoS metrics that can be fulfilled at the transport layer are the following:

- Maximizing end-to-end reliability.
- Bandwidth/throughput fairness.
- Minimizing congestion probability.
- Minimizing energy consumption.

QoS mechanisms that can be used at the transport layer are the following:

- Loss recovery: Consists of two phases: (i) Loss detection and notification (continuity of sequence number is used to detect packet loss); and (ii) Retransmission recovery (can be performed end-to-end or hop-by-hop).
- Congestion control: Uses following mechanism to control congestion: congestion detection, congestion notification, and congestion mitigation and avoidance [25].
- Flow control: Ensures that the overall transmission rate of the sender never exceeds the reception rate of the receiver. There are two types of flow control mechanisms: closed-loop flow control and open-loop flow control [26].
- Source prioritization: Prioritizes sensed information based on their information content priority.

In [27, 28], authors described a novel transport layer protocol based on the source prioritization for QoS provisioning. Proposed protocol supports data reliability and congestion control and is composed of two modules:

1. Congestion control module: It is used to detect, inform and mitigate the congestion in the network and for calculating congestion index. Congestion index is used to measure the severity of the congestion in the network.
2. Prioritization and reliability module: It receives incoming data packets from all available sources, retains them at selected intermediate motes for some defined interval time, and prioritizes them based on their information content priority. Afterwards, data forwarding is based on source priority and Time To Leave (TTL) value. Furthermore, it is responsible for resending data packets upon receiving the Negative Acknowledgment (NACK) from the sink.

Simulation testing of the proposed protocol has been performed into three possible scenarios: (i) With no prioritized enabled storage; (ii) Complete prioritized enabled storage; and (iii) Distributed prioritized enabled storage. Distributed prioritized enabled storage and data forwarding, showed better results in-terms of average throughput and average data packet drop, in comparison with other two scenarios. However, more performance evaluation is desirable in order to compare proposed protocol with similar protocols and to examine trade-off between QoS and battery life.

In addition, several transport protocols with QoS support can be found in [29, 30, 31]. Wireless Modular Transport Protocol (WMTP) [29] uses a modular architecture and provides different features, namely congestion control, fairness, reliability, optionally integrated service-discovery and QoS. However, only the fairness feature was evaluated through a series of tests. Experimental results show that WMTP protocol ensures throughout fairness and minimizes congestion probability with minimal energy cost. POWER-SPEED [30] achieves an energy-efficient data transport for delay-sensitive event reporting in real-time WSANs. It avoids the overhead of control packets by selecting the next-hop neighbor based on the downstream path quality and the latency-bound requirement of packets. Therefore, it maintains QoS requirement in timeliness domain. In [31], authors presented a protocol that uses a rate control mechanism to adjust the transmission rate of each sensor node based on the congestion degree in the network. It supports QoS by controlling congestion and providing reliability in packet delivery.

Open Research Issues and Challenges

As one can surmise, the biggest challenge for QoS provisioning in WSNs is how to provide the desired QoS to users and applications and in the same time preserve energy of WSNs and consequently increase network lifetime. Although energy efficiency and network lifetime are sometimes parts of QoS requirements, they are mostly considered as individual metrics.

To date, the majority of QoS aware layered protocols consider QoS only as layer specific isolated set of problems and lower layers performance are mostly based on assumptions. However, QoS provisioning in the network and transport layers cannot be accomplished without support from the MAC layer.

MAC layer QoS support in WSNs particularly focuses on scheduling and channel allocation to support upper layer services, such as routing and data aggregation. Furthermore, since retransmissions are handled in the MAC layer in case of a transmission failure, upper layers may need to query the MAC layer in order to obtain information on the congestion state and the link quality. Most routing solutions utilize this information for delay estimation [32].

MAC level QoS support is mostly limited to the policies implementing scheduling, channel allocation, buffer management, error control, and error recovery [32]. Therefore, MAC layer cannot independently support all desired QoS metrics. For example [25], since MAC protocol determines how packets are transmitted within 1 – hop, it has an impact on energy efficiency and QoS. A routing protocol can improve reliability and QoS through optimal path selection. However, neither routing nor MAC protocols can independently address any of these problems satisfactorily.

Transport layer protocols are highly depended on network layer performance. For example [25], since certain transport protocols in WSNs assume that single path routing is used in network layer, issues such as congestion and fairness could arise if the network layer supports the multi-path routing.

Conjunction of different layer protocols could provide improved QoS support. In [14], authors developed a QoS-aware MCMAC protocol for WBAN. However, after they applied their novel dynamic priority assignment strategy for data routing [33], on the top of the MCMAC layer, a significant improvement in the achieved QoS occurred.

QoS metrics such as maximizing overall throughput and minimizing end-to-end delay cannot be accomplished with layered QoS approach. In order to meet the above requirements, QoS provisioning must be enabled in each WSN layer. Furthermore, higher efficiency could be accomplished with sharing important information among all layers in WSNs. This can be accomplished with cross-layer approach that can jointly optimize MAC, network and transport layers performance.

4. CROSS-LAYER APPROACH FOR QOS PROVISIONING IN WSNS

The QoS provisioning goal for layered and cross-layer protocols is the same: Providing the desired QoS level to applications and users while decreasing energy consumption, and consequently prolonging network lifetime. The only difference is in the approach used for achieving the desired QoS. The layered approach investigate the optimization of protocols in individual layer, which can lead to performance improvements and QoS provisioning in this particular layer, while the cross-layer approach provide QoS by the jointly optimizing and melting all layer protocols into a single one.

The majority of the early research efforts have focused on enabling QoS in individual layers. However, QoS provisioning in WSNs involves all layers of the communication protocol stack and therefore, cross-layer solution arises as a promising method.

Motivation for the cross-layer approach is as follows: Conjunction of individual and isolated QoS mechanisms could cause conflicts in QoS provisioning goals; Because of dependencies between layers, individual layer QoS provisioning is an inefficient solution; Individual layer cannot guarantee overall QoS provisioning.

Since cross-layer solutions dispose with information of all layers, the main advantage of cross-layer approach is in optimization of overall performance of the WSNs and providing overall QoS provisioning. Primary QoS metrics that can be fulfilled with the cross-layer approach are:

- Decreasing overall energy consumption.
- Maximizing network lifetime.
- Maximizing network throughput.
- Minimizing end-to-end delay.
- Maximizing overall reliability.

Other QoS metrics, such as minimizing collisions, minimizing congestion, providing effective sample rate, etc., are supported through the primary QoS metrics.

In [34], authors proposed novel cross-layer design architecture for QoS support in WMSNs, which jointly optimizes application, network, MAC and link layers to achieve desired QoS. The QoS of multimedia data can be characterized by four parameters: delay jitter, end-to-end deadline, bandwidth and reliability over unreliable medium. The main goal is to maximize the number of video stream realizations considering per hop bandwidth, delay and reliability constraints, such that packets are delivered under probabilistic hops count limit. Proposed design architecture consists of:

1. Traffic classifier module: Classifies the types of frames and assigns the priorities.
2. Route classifier module: Implements the novel Source Directed Multiple Path (SDMR) routing

algorithm and chooses an appropriate path for frame delivery.

3. MAC interface: Maps the packets according to their priorities.

4. Multi-rate link adaptation: Dynamically chooses the appropriate transmission mode directed by the network layer to provide the required bandwidth subject to the link reliability.

SDMR is used for directed routing from the source to the sink. It selects forwarding node by computing the resistance of a node based on residual energy and distance from the path origin line. It can be dynamically changed based on application requirements. Furthermore, SDMR provides an estimation of the maximum number of hops on the basis of node density. In order to meet the bandwidth constraints, source admission control is incorporated into each node. Before data transmission it sends first request packet to verify the transmission route. In order to minimize the number of delayer packets, frames are sorted according to their deadlines.

Simulation results show that proposed cross-layer design architecture, compared to the fixed source encoding and single mode transmission, supports a higher number of video sources. Furthermore, it can be seen that increasing number of video sources does not significantly increase the average end-to-end packet delay. However, impact on the energy consumption and consequently network lifetime of proposed cross-layer design architecture is unknown.

In [35], authors developed QUAlity-of-service-capable clusTer-based Time-shared ROuting-assisted MAC protocol (QUATTRO), which uses collaboration of the MAC and routing protocols. Setup process of QUATTRO includes:

1. Route discovery and assignment of a weight value to each route.

2. Route selection and reservation of resources between sensing nodes and sink on this route.

3. Cluster formation.

4. Activity windows assignment to the cluster in such way that they do not interfere with each other.

The key for satisfying QoS requirements is route selection that must ensure enough resources. Consequently, the proposed cross-layer protocol can guarantee the desired QoS and still provide energy conservation by avoiding collisions and by better utilization of sensor nodes idle state. As cluster heads have higher energy consumption, setup will be repeated periodically in order to switch roles between cluster heads and nodes. Performance evaluation was conducted using two set of simulations with different number and density of nodes. Results showed that protocol overhead observed in terms of configuration time and transmitted control messages is very reasonable. However, important metrics such as energy consumption, network throughput and end-to-end delay, were not observed.

In addition, several cross-layer methods with QoS support can be found in [36, 37, 38]. Detailed analysis of the cross-layer routing model for QoS in real-time wireless ad hoc sensor networks is performed in [36]. Cross-layer optimization is based on analytical Multivariate Point Process (MVPP) models of real-time packet flows for heterogeneous sensors on routes. The constructed MVPP models are derived from earlier models for Mobile Ad Hoc Networks (MANETs) and they address both QoS-based and energy-efficient routing. Although analytic analysis of MMVPP modes is described, experiments and performance evaluations are not conducted. Therefore, real contribution of the proposed cross-layer routing model remains an open question. In [37], authors developed cross-layer communication architecture, which enables the QoS support in Ultra Wide Band (UWB) WMSNs. It controls and leverages interactions among physical, MAC and network layer and shares the transmission medium among devices, schedules transmissions of data packets and assigns data rates to different flows based on the application requirements. It is based on time-hopping impulse radio UWB communications. Furthermore, they developed simulation tools and show that proposed cross-layer communication architecture satisfies application QoS requirements such as number of lost packets and maximum delay time. In [38], authors created cross-layer optimization protocol architecture for the QoS support, based on middleware for WSNs. The objective of this design is to meet different QoS application requirements by reducing energy consumption, and improving transmission efficiency and robustness to faults and failures of WSNs. To meet these objectives, authors developed a new framework that consists of three main modules: QoS ontology, QoS agent, and sensor nodes QoS protocol stack. QoS protocol stack is organized as two shared databases across physical, MAC, network and application layers. The proposed cross-layer QoS optimization framework can enable interfacing with existing protocols and can be adopted in any WSN. However, to prove the efficiency of proposed cross-layer design architecture, experiments and performance evaluation should be conducted.

Open research issues and challenges

Since QoS provisioning in WSNs involves all layers of the communication protocol stack, traditional layered network design is not an effective method for providing overall QoS support in WSNs. Cross-layer approach seems to be a better and more efficient solution, since it does not has restrictions as layered approach.

Recent studies show that the cross-layer approach is still developing and QoS provisioning improvements compared to the layered approach are not clearly visible in the above papers. Papers described above present different cross-layer methods for QoS provisioning in WSNs but they lack of experiments, performance evaluations and especially performance comparisons to layered solutions. Therefore, one of the open research issues is benchmarking of both layered and cross-layer QoS provisioning approaches in order to obtain objective and measurable comparison results.

Since energy consumption is one of the main restrictions in WSNs, there is a need for simple and energy effective QoS provisioning methods. Cross-layer methods use parameters from different layers from the communication protocol stack, and consequently they are more complex than layered QoS mechanisms. Therefore, a big challenge is effective exchange of information between different layers that does not consume a lot of resources and is easy to implement.

Not all cross-layer methods use all WSNs layers for QoS provisioning. For example, in [35], authors use only cross-layer collaboration of the MAC and routing protocols for QoS provisioning. However, including more layers into cross-layer methods, result with better QoS provisioning, due to higher number of supported parameters.

Only cross-layer protocol described in [38], enables interfacing with existing protocols. More effort should be directed towards the creation of mechanisms that supports and can operate with existing WSNs protocols. Furthermore, neither of the cross-layer mechanisms considers utilization of several existing layered protocols, in order to obtain complete cross-layer solution. Therefore, one of the challenges lies in efficient conjunction of proved layered protocols from Section 3 into cross-layer solution.

Modular based architecture can be found in some layered protocols [18, 29], but cross-layer mechanisms are not built on this principle. Modular or component based architecture provides more space for optimization and implementation of new features. Therefore, it should be taken into consideration while building QoS cross-layer mechanisms.

Since more WSNs are used for tracking objects, animals, humans and vehicles, cross-layer QoS mechanisms should also consider sensor and node mobility.

Although a cross-layer approach has huge potential to become the most efficient solution for the QoS provisioning in WSNs, there are still numerous issues and challenges that need to be overcome.

5. REVIEW OF THE QOS PATENTS IN WSNS

Since extensive research on the concept of the QoS in WSNs has been performed in last five years, currently there are not a large number of patents that are dealing with this issue. All available patents in this area are described below. In the coming years, a large increase in the number of the similar patents is expected.

With today's technologies intelligent and automatic world is reality. Presented invention in US20110035491 [39] describes a Wireless Integrated Network Sensor Next Generation (WINS NG) network with various capabilities that could change the areas of transportation, manufacturing, health care, environmental monitoring, and safety and security. This invention relates to the field of intelligent networks that include connection to the physical world and provide distributed network and Internet access to sensors, controls, and processors that are embedded in equipment, facilities and the environment. With combining new technologies and modular design in a compact system, the WINS NG networks are more efficient, have lower power consumption and provide advanced sensing, control and processing capabilities. One of the main benefits of proposed invention is storing of all available information about the physical world in a database. This enables data manipulation, classification and intelligent decision making. Furthermore, to meet QoS requirements and priorities of end user for information, WINS NG network is taking into account constraints on storage, communications bandwidth, processing capabilities and energy. To reduce communication and lower energy consumption, WINS NG database addresses query optimization. Queries are managed such that proper decisions are taken regarding the need to communicate with distant nodes. Furthermore, node-to-node queries enable nodes to improve quality of a decision by cooperative methods, comparing results with the stored data in the neighboring nodes.

US20117948945 [40] details a different methods for providing improved message delivery for higher priority nodes or messages. One example of using the proposed method is shown in Fig. (**1**). The method includes identifying priorities associated with nodes or messages. High priority nodes or messages get needed time slots for data delivery while low priority communication is ignored or low priority nodes are signaled not to communicate. Other proposed solution for low priority nodes is to use different frequencies for communication but this could be difficult to achieve as WSNs have limited communication capabilities. This method is intended for using primary in industrial wireless networks but it could be used in any other wireless network including WSN that need prioritization of nodes or messages. The main benefit of the described invention is that in wireless networks

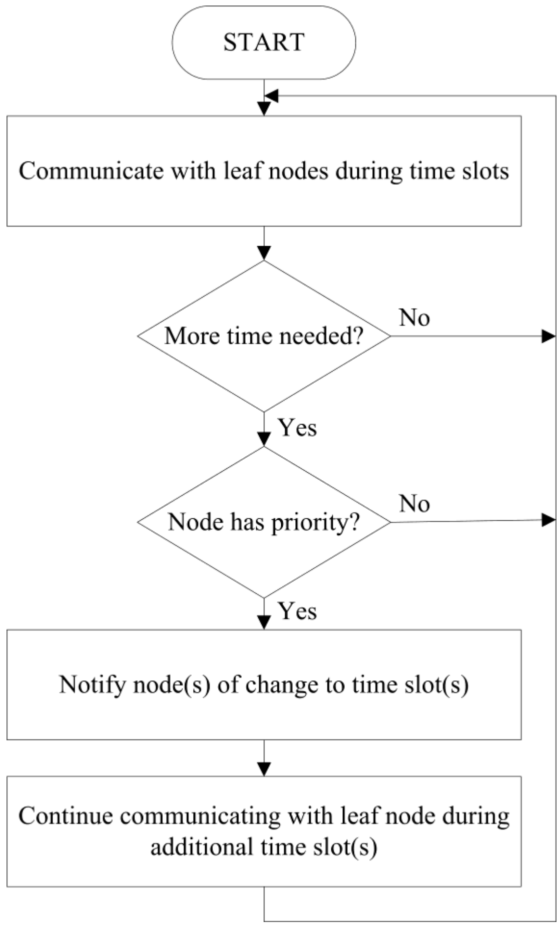

Fig. (1). Method for providing improved message delivery

where underlying wireless protocols (such as in physical, MAC or network layer) are unaware of data priority requirements and are providing the same QoS to all communication, proposed method can be applied and can provide distinct QoS-aware levels to different nodes in the system. However, contribution of this patent is limited since communication is divided in only two categories, low and high, and situations with high number of high priority communication at the same time are not included.

WO2010100446 [41] presents the invention for allocating resources in WSNs. There are several aspects of the presented invention and they are all based on streaming allocation. Network devices are sending requests for streaming towards a coordinator of the network. After receiving requests, the coordinator must distinguish the emergency request from the non-emergency request. Emergency condition could be determinate based on parameters values in different parts of the network. The coordinator granting each the request by scheduling one of the QoS levels as shown in Table **2**. Therefore, data streaming has guaranteed parameters like delay time and the size of the data pipe. Presented invention could be used primary in medical applications but it could be also used in other emergency or industrial applications.

US20100142422 [42] outlines a technique for cooperative packet routing in WSNs. When sending packets from a source to a base station, they are going through number of so-called transient nodes. After receiving the packet, the transient node determines the amount of its remaining power and if this value is less than the predefined energy threshold, the transient node discards the received packet. Energy threshold is the minimum energy required to perform certain predefined tasks. However, if the amount of remaining power in the transient node is greater than or equal to the predefined energy threshold, the transient node implements a set of cooperative packet routing operations for conditional re-transmission of the packet to the base station. Every transient node must receive a base station acknowledgment before the timer counter times out, otherwise the received packet is retransmitted. The effects of various parameters and their impact on the system performance and the QoS have been tested in simulation. The parameters include scale factor, energy threshold, duplicate counter, buffer size, timer value, mean inter-arrival time and number of nodes. Predetermined scalar factor value determines QoS levels in the application area. There is an optimal value for the scalar factor that preserves energy and memory with minimum delay.

US20090245224 [43] details the method that provides the QoS in wireless or sensor networks by determining a class or type of the service for transmission of one or more messages. One of the possible QoS processes is shown below:

Start

1. Determine the class of the service.
2. Adjust the maximum packet length.
3. Allocate message time slots.
4. Set the guard band size and frequency of resynchronization.
5. Transmit one or more messages.

End

The first step is determining class of services as different classes of services have different QoS needs. Adjusting maximum packet length (step 2) and allocating message time slots (step 3) are based on the determined class of service (step 1). The guard band size and the frequency of resynchronization (step 4) may be set based on one or more factors, including step 1. Therefore, messages transmission (step 5), which can be performed in any order, is based on steps 2, 3 and 4. The QoS method can be applied to Connectionless Scheduling Protocol (CSP). CSP is cross-layer MAC that produces near optimal channel utilization with near optimal energy utilization by using pseudorandom

Table **2** Classification of the bit rate and QoS levels.

Streaming classes	Medical	Emergency	Bit rate	QoS levels
1	Yes	Yes	Lowest delay in response to the required delay. Highest available data rate pipe in response to the required bit rate.	Highest
2	No	Yes	Lowest delay in response to the required delay. Highest available data rate pipe in response to the required bit rate.	
3	Yes	No	Required delay if possible. Required data rate pipe if available.	Middle
4	No	No	Required delay if possible. Required data rate pipe if available.	Low

message scheduling approach. The QoS method uses configurable parameters in the CSP to provide QoS to different classes of network traffic, priorities of traffic within classes, or priorities of users or nodes sending or receiving traffic. These parameters are number of Message Start Times (MST) based channel access and Maximal Packet Length. Higher priority users/classes or classes with more strict latency requirements may be given more MST schedules and longer Maximum Packet Length.

US20090154407 [44] proposes a solution for the high priority data delivery problem. In most cases WSNs contain various kinds of data that are typically classified into low priority data and high priority data but all kinds of data are delivered through one path. Problems occur if this path is cut since in this case conventional methods establish a new path but cannot ensure that high priority data will be reliably delivered. Therefore, the proposed solution to this problem is the formation of more reliable paths form a source node to destination node. The proposed method in [44] can enhance the reliability and QoS of the clustering topology-based WSNs with various kinds of data and limited resources. Furthermore, effective services are provided depending on the QoS, data types and priorities. This is accomplished by effectively performing routing and allocating resources in WSNs.

Operations of an initializing step of the proposed method are:

Start

1. Form the cluster and elect the cluster head.
2. Select the routing path between the cluster head and the sensor node.
3. Select the frame length.
4. Constitute the time slot resource allocation table for the communication between cluster heads.
5. Exchange time slot resource allocation table between neighboring cluster heads.

End

First, it is necessary to form clusters and elect a cluster head (step 1). Cluster heads manage the cluster and deliver information to an upper cluster or a neighboring cluster. Selection of routing paths between cluster heads and sensor nodes must be done according to QoS requirements of the network (step 2). Routing paths must guarantee a reliable communication even if an error occurs. Frame length is calculated based on number of elements of the network, a distribution method employed and a routing path (step 3). Formation of the time slot resource allocation table should minimize interference between the clusters and maximize the performance of the network (step 4). Initialization is ended after time slot resource allocation table is exchanged with 1-hop neighboring cluster head.

Operations that follow initialization are:

Start

1. Initialize the routing path between clusters.
2. Allocate resource to the sensor node requesting resource allocation based on the resource allocation table.
3. Sensor node transmitting data to the resource.
4. Collect and classify data.
5. Negotiate channel reuse.
6. Communication.

End

After initialization (step 1) resources are allocated to internal nodes of a cluster (step 2). Through the allocated resources sensor node data are transmitted to the cluster head (step 3). As one of the major causes of inefficient use of resources is duplicated transmission of data, in step 4 data types are classified. Internal nodes could get more than the allocated resources through a channel reuse negotiation with a cluster head (step 5). Reliable and QoS capable communication is established in step 6.

Due to the fact that WSNs often cover huge areas, large numbers of nodes must be used. Since wireless sensor nodes have limited sensing radius they should be distributed in such a manner to cover the whole target field. Coverage of the target field is a measure of the QoS and it must be guaranteed by the WSN. Coverage holes could arise due to the poor node distribution or due to node failure. WSNs should have coverage verification mechanisms to report cover holes. US20090257373 [45] claims a method to improve the coverage verification in WSNs. Coverage holes are detected by a coverage hole detection process:

Start

1. Sensor node initially obtains the distance to neighboring nodes in transmission radius.
2. Sensor node distributes distances to neighboring nodes.
3. Sensor node performs cyclic segment sequence algorithm.
4. Sensor node establishes the individual coordinate system and determines relative location of neighboring nodes (r-map).
5. Sensor node verifies k-coverage of sensing border by using r-map coordinates.

End

The Coverage holes detection process does not require information about the location of sensor nodes in the WSN, rather sensor nodes establish its own coordinate system (step 4). Segment sequence algorithm (step 3) identify border segments of a sensing border wherein each of border segments comprises a section of the sensing border that is covered by a sensing radius of at least one of neighboring nodes. Step 5 verifies if sensing border is covered more than once.

US20077277414 [46] outlines a method for dynamically reconfiguration of WSN based on available energy at each sensor. Method steps are:

Start

1. Deploy sensors.
2. Determine the geographic location of each sensor.
3. Cluster sensors to minimize the energy consumption.
4. Set the network data route.
5. Model energy available at each sensor.
6. Detect environmental parameters and relay data.
7. Reset network data routes.

Continue (to step 5)

When the sensor battery level drops to the predetermined value, the network topology is dynamically adapted in order to minimize energy consumption, extend the network lifetime while ensuring QoS for the data transmission. However, this method is limited only to extending network lifetime and other QoS parameters are not included. Furthermore, every rerouting consumes energy of all nodes and a new route could be much longer than the previous route which could increase delays and lower network bandwidth.

The inventor of US20060178150 [47] proposes a technique for adding a new sink in the existing WSN with two main functions:

- Providing a method of adding a new sink without tree reconfiguration.
- Minimizing energy consumption when a new sink is added to the dissemination tree in a WSN.

When a new sink as added to the WSN, the method configures the dissemination tree and determines an optimal path having less energy consumption. Energy consumption of the proposed invention is compared with the energy consumption versus the number of sinks of the two conventional three configuration schemes, Two-Tier Data Dissemination (TTDD) and Direct Diffusion (DD), and it is shown that proposed invention reduces total energy consumption in WSNs. Furthermore, since the path determination is made taking into account a delay limit as well as the distance between a source and a destination, QoS is also satisfied.

6. CURRENT & FUTURE DEVELOPMENTS

Generally, guaranteeing a certain QoS level in WSN is a challenging issue due to the limited available resources and capabilities, such as energy, memory, bandwidth and processing capabilities, unpredictable nature of wireless links and often huge number of sensor nodes in WSN. Current development of WSNs indicates that they are becoming increasingly complex and consequently users and applications require more bandwidth, lower delays and increasing reliability. Therefore, QoS support is becoming one of the key factors of WSNs.

Major research efforts in WSNs domain have resulted in many different QoS provisioning methods. In this study, we surveyed QoS provisioning in WSNs from two different approaches: layered and cross-layer, and analyzed existing methods and patents. The majority of the early research efforts have focused on enabling QoS in individual layers. Existing QoS provisioning protocols in MAC, network and transport layer consider QoS as layer specific isolated set of problems. Furthermore, they are highly depended on performance of other layers and therefore, cannot guarantee overall QoS provisioning. However, QoS provisioning is achieved by using various mechanisms that are supported at individual layer. MAC layer protocols use time slots reservation procedures and data prioritization. Furthermore, they achieve resilience to topology change and supports mobile nodes. Routing protocols in network layer mostly use multipath routing or traffic differentiation for QoS provisioning. The most important mechanism for transport protocols is congestion control, which can maximize reliability and provide throughput fairness. Since cross-layer methods could dispose with information from all layers and can provide overall QoS provisioning, they have huge potential to become most efficient solution for the QoS provisioning in WSNs. However, surveyed papers do not prove the expectations, since they lack of experiments, performance evaluation and performance comparison to layered solutions. Additionally, there are not a large number of patents in this domain. Nevertheless, existing patents are covering various aspects of QoS provisioning and they are mostly based on QoS provisioning for high priority data, data prioritization, resource allocation, coverage verification and dynamically topology adaptation. Due to the increasing number of scientific papers dealing with QoS provisioning in WSNs, rapid development is obvious. Therefore, it can be assumed that a large number of new patents that will give new and improved methods for the successful implementation of QoS as a standard part of WSNs will emerge in the future.

Currently, QoS provisioning is the most important in real-time, multimedia and critical WSNs that require a guaranteed performance in order to function properly. However, due to increasing number of users and applications, soon will not be enough to have QoS only as the option in WSNs, rather QoS must become a standard part of WSNs.

As described in Section 2, future developments of QoS support in WSNs should cope with following challenges:

- Limited WSN resources and capabilities.
- Unstructured node deployment.
- Dynamic network topology.
- Scalability.
- Multi-source multi-sink systems.
- Various types of applications.
- Various traffic types.
- Wireless link unreliability.
- Data redundancy.

Some papers propose the implementation of middleware to ensure the desired QoS. Middleware should contain detailed information about WSN performance and QoS characteristics, in order to provide the desired QoS to applications or users. Novel QoS provisioning methods should achieve resilience to frequent changes in WSNs, which can occur due to changes in network topology, node mobility, unbalanced traffic, node failure and wireless link unreliability. Therefore, they should be dynamic and adjust QoS provisioning to network conditions and available resources. However, these dynamic methods should not consume high amounts of energy during the adjustment process. As described in [5], one of the important aspects that should be also extensively studied is feedback mechanisms to adjust protocol behavior. Feedback obtained from the end nodes could improve the application level QoS guarantees and total number of applications supported in real-time WSNs.

Furthermore, since the vast majority of WSNs nodes have no permanent power sources, QoS protocols should include energy efficiency as one of the main QoS parameters. Since energy efficiency is crucial for WSNs lifetime, in classic WSNs it should have greater weight than other parameters. However, in real-time, multimedia and critical WSNs, more weight should be put on bandwidth, reliability and response time. Since QoS parameters such as bandwidth, delay, jitter and packet loss are inversely proportional to energy consumption, there is a need to trade-off between energy consumption and QoS provisioning.

In conclusion, both layered and cross-layer approaches can be effectively used for QoS provisioning in WSNs. However, due to design architecture, the cross-layer approach provides more space for optimization, improving performance and QoS provisioning and has huge potential to become most efficient solution for the QoS provisioning in WSNs. According to the current state in this domain, we can conclude that more research is needed to improve current cross-layer approach.

7. CONFLICT OF INTEREST

Authors have no conflicts of interest to declare.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

[1] Dohler M. Wireless Sensor Networks: The Biggest Cross-Community Design Exercise To-Date. Recent Patents on Computer Science 2008; 1: 9-17.

[2] Yick J, Mukherjee B, Ghosal D. Wireless Sensor Network Survey. Computer Networks (Elsevier) 2008; 52: 2292-39.

[3] Chen D, Varshney PK. QoS Support in Wireless Sensor Networks: A survey. *Proceedings of the 2004 International Conference on Wireless Networks*. Las Vegas, USA, June 21-24, 2004.

[4] Wang Y, Liu X, Yin J. Requirements of Quality of Service in Wireless Sensor Network. *Proceedings of the International Conference on Networking, International Conference on Systems and International Conference on Mobile Communications and Learning Technologies.* Morne, Mauritius, April 23-29, 2006.

[5] Vural S, Tian Y, Ekici E. In: A. Boukerche, Eds. QoS-Based Communication Protocols in Wireless Sensor Networks. New York: John Wiley & Sons 2008: 365-35.

[6] Vali D, Paskalis S, Kaloxylos A, Merakos L. A Survey of Internet QoS Signaling. IEEE Communications Surveys & Tutorials 2004; 6: 32-12.

[7] Xia F. QoS Challenges and Opportunities in Wireless Sensor/Actuator Networks. Sensors 2008; 8: 1099-12.

[8] Chen J, Díaz M, Llopis L, Rubio B, Troya JM. A Survey on Quality Of Service Support in Wireless Sensor and Actor Networks: Requirements and Challenges in the Context of Critical Infrastructure Protection. Journal of Network and Computer Applications 2011; 34: 1225-15.

[9] Li YJ, Chen CS, Song YQ, Wang Z. Real-time QoS Support in Wireless Sensor Networks: A Survey. *Proceedings of the 7th International Conference on Fieldbuses & Networks in Industrial & Embedded Systems*. Toulouse, France, November 7-9, 2007.

[10] Cheng C, Tian B, Li Y, Yao O. Data Aggregation Technologies of Wireless Multimedia Sensor Networks: A Survey. *Proceedings of the 2010 IEEE International Conference on Vehicular Electronics and Safety*. QingDao, China, July 15-17, 2010.

[11] Yigitel MA, Incel OD, Ersoy C. QoS-aware MAC Protocols for Wireless Sensor Networks: A survey. Computer Networks (Elsevier) 2011; 55: 1982-23.

[12] Zogovic N, Dimic G, Bajic D. Wireless Sensor Networks: QoS Provisioning at MAC and Physical Layers. *In 17th Telecommunications Forum TELFOR*. Serbia, Belgrade, November 24-26, 2009.

[13] On J, Jeon H, Lee J. A Scalable MAC Protocol Supporting Simple Multimedia Traffic QoS in WSNs. International Journal of Distributed Sensor Networks 2011; In Press (Accepted 25 May 2011).

[14] Nabi M, Blagojevic M, Geilen M, Basten T, Hendriks T. MCMAC: An Optimized Medium Access Control Protocol for Mobile Clusters in Wireless Sensor Networks. *Proceedings of the 7th Annual IEEE Communications Society Conference on Sensor Mesh and Ad Hoc Communications and Networks.* Boston, USA, June 21-25, 2010.

[15] Huang R, Song WZ, Xu M, Shirazi B. Localized QoS-aware Media Access Control in High-fidelity Data Center Sensing Networks. *Proceedings of the International Conference on Green Computing*. Chicago, USA, August 15-18, 2010.

[16] Kim H, Min SG. Priority-based QoS MAC Protocol for Wireless Sensor Networks. *Proceedings of the IEEE International Symposium on Parallel & Distributed Processing*. Rome, Italy, May 23-29, 2009.

[17] Ehsan S, Hamdaoui B. A Survey on Energy-Efficient Routing Techniques with QoS Assurances for Wireless Multimedia Sensor Networks. IEEE Communications Surveys & Tutorials 2011; 99: 1-14.

[18] Djenouri D, Balasingham I. Traffic-Differentiation-Based Modular QoS Localized Routing for Wireless Sensor Networks. IEEE Transactions on Mobile Computing 2011; 10: 797-13.

[19] He T, Stankovic JA, Lu C, Abdelzaher TF., A Spatiotemporal Communication Protocol for Wireless Sensor Networks. IEEE Transactions on Parallel and Distributed Systems 2005; 16: 995-12.

[20] Felemban E, Lee CG, Ekici E. MMSPEED: Multipath Multi-Speed Protocol for QoS Guarantee of Reliability and Timeliness in Wireless Sensor Networks. IEEE Transactions on Mobile Computing 2006; 5: 738-17.

[21] Or-Rashid MM, Razzaque MdA, Alam MM, Hong CS. Multi-Constrained QoS Geographic Routing for Heterogeneous Traffic in Sensor Networks. IEICE Transactions on Communications 2010; 91B: 2589-13.

[22] Houngbadji T, Pierre S. QoSNET: An Integrated QoS Network for Routing Protocols in Large Scale Wireless Sensor Networks. Computer Communications (Elsevier) 2010; 33: 1334-9.

[23] Ben-Othman J, Yahya B. Energy Efficient and QoS Based Routing Protocol for Wireless Sensor Networks, Journal of Parallel and Distributed Computing, 2010; 70: 849-9.

[24] Cobo L, Quintero A, Pierre S. Ant-based Routing for Wireless Multimedia Sensor Networks Using Multiple QoS Metrics, Computer Networks (Elsevier) 2010; 54: 2991-20.

[25] Wang C, Li B, Sohraby K. In: Zhenog J, Jamalipour A, Eds. Transport Protocols and Quality of Service. New York: John Wiley & Sons, Inc. 2009: 343-26.

[26] Munishwar VP, Tilak SS, Abu-Ghazaleh NB. In: Misra S, Woungang I, Misra SC, Eds. Congestion and Flow Control in Wireless Sensor Networks. London: Springer 2009: 205-24.

[27] Sharif A, Potdar V, Rathnayaka AJD. Prioritizing Information for Achieving QoS Control in WSN. *Proceedings of the 24th IEEE International Conference on Advanced Information Networking and Applications*. Perth, Australia, April 20-23, 2010.

[28] Sharif A, Potdar V, Rathnayaka AJD. Priority Enabled Transport Layer Protocol for Wireless Sensor Network. *Proceedings of the 3rd International Workshop on RFID & WSN and its Industrial Applications.* Perth, Australia, April 20-23, 2010.

[29] Pedrosa LD, Rocha RM. WMTP - A Modular WSN Transport Protocol: The Fairness Module. *Proceedings of the New Technologies, Mobility and Security*. Tangier, Marocco, November 5-7, 2008.

[30] Zhou Y, Ngai ECH, Lyu, MR, Liu J. POWER-SPEED: A Power-Controlled Real-Time Data Transport Protocol for Wireless Sensor-Actuator Networks. *Proceedings of the IEEE Wireless Communications and Networking Conference*, Hong Kong, March 11-15, 2007.

[31] Yaghmaee MH, Adjeroh D. A Reliable Transport Protocol for Wireless Sensor Networks. *Proceedings of the International Symposium on Telecommunications*, Tehran, Iran, August 27-28, 2008.

[32] Basaran C, Kang KD. In: Misra S, Woungang I, Misra SC, Eds. Quality of Service in Wireless Sensor Networks. London: Springer 2009: 305-17.

[33] Nabi M, Blagojevic M, Geilen M, Basten T. Dynamic Data Prioritization for Quality-of-Service Differentiation in Heterogeneous Wireless Sensor Networks. *Proceedings of the 8th Annual IEEE Communications Society Conference on Sensor Mesh and Ad Hoc Communications and Networks.* Salt Lake City, USA, June 27-30, 2011.

[34] Shah, GA, Liang W, Shen X. Cross-Layer Design for QoS Support in Wireless Multimedia Sensor Networks. *Proceedings of the IEEE Global Telecommunications Conference*. Miami, USA, December 6-10, 2010.

[35] Ruiz J, Gallardo JR, Villasenor-Gonzalez L, Makrakis D, Mouftah HT. QUATTRO: QoS-capable Cross-layer MAC Protocol for Wireless Sensor Networks. *Proceedings of the 28th IEEE Conference on Global Telecommunications*, Honolulu, USA, November 30 – December 4, 2009.

[36] Hortos WS. Analysis of Cross-layer Routing Protocols for Quality Of Service in Real-time Wireless Ad Hoc Sensor Networks. *Proceedings of the 6th Annual International Conference on Mobile and Ubiquitous Systems Networking and Services MobiQuitous*. Toronto, Canada, July 13-16, 2009.

[37] Melodia T, Akyildiz IF. Cross-layer Quality of Service Support for UWB Wireless Multimedia Sensor Networks. *In Proceedings of the 2008 IEEE Conference on Computer Communications*. Phoenix, USA, April 13-18, 2008.

[38] Cai WY, Yang HB. Cross-layer QoS Optimization Design for Wireless Sensor Networks. *Proceedings of the IET Communications Conference on Wireless, Mobile and Sensor Networks*. Shanghai, China, December 12-14, 2007.

[39] Gelvin, D. C., Girod, L. D., Kaiser, W. J., Merrill, W. M., Newberg, F., Pottie, G. J., et al. Method for internetworked hybrid Wireless Integrated Network Sensors (WINS), US20110035491 (**2011**).

[40] Budampati, R. S., Method and apparatus for improved message delivery for higher priority nodes or messages in an industrial wireless network, US20117948945 (**2011**).

[41] Abedi, S., Chebbo, H. Improvements to wireless sensor networks. WO2010100446 (**2010**).

[42] Al-Wakeel, S. S., Al-Nabhan, N. A. Cooperative packet routing for wireless sensor networks. US20100142422 (**2010**).

[43] Iyer, S. K., Evans, S. C., Tomlinson H. W. Jr., Deb, B., Kuthethoor, G., Weerakoon, I. P. Method and apparatus for providing quality of service in wireless networks and sensor networks. US20090245224 (**2009**).

[44] Jeong, W. C., Kim, N. S., Pyo, C. S., Chung, J. M., Cho, H. W., Jin, K. Y. Method of performing routing and allocating resources in wireless sensor network. US20090154407 (**2009**).

[45] Bejerano, Y. Methods and apparatus for coverage verification in a wireless sensor network. US20090257373 (**2009**).

[46] Younis, M. F., Youssef, M. A., Arisha, K. A., Energy aware network management, US20077277414 (**2007**).

[47] Kim, H. S. Method of transmitting data with minimum energy consumption in a wireless sensor network, US20060178150 (**2006**).